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DEFENSE SYSTEMS MANAGEMENT COLLEGE

VIRTUAL PROTOTYPING:
Concept to Production

Report of the
DSMC 1992-93
Military Research Fellows

Lieutenant Colonel (P) Albert B. Garcia, USA

Colonel (Sel) Robert P. Gocke, Jr., USAF

Colonel Nelson P. Johnson, Jr., USA

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God and the soldier all men adore,
in time of trouble and no more.
For when war is over and all things
righted, God is neglected and the old
soldier slighted.

— **Lines found engraved on an old sentry box in Gibraltar**

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PREFACE

This study represents the combined efforts of three military Research Fellows participating in an 11-month Senior Service College Research Fellowship program sponsored by the Under Secretary of Defense (Acquisition).* The fellowship program has two purposes: first, to provide professional military education for selected officers from the Army, Navy and Air Force; second, to conduct research in a subject of vital interest to the U.S. defense acquisition community. In keeping with its role as the center for systems management education in the Department of Defense (DOD), the Defense Systems Management College (DSMC), cooperating with the Harvard University Graduate School of Business, provided the means for conducting this study. The fellowship program includes the 12-week resident Program for Management Development (PMD) course at Harvard University, Cambridge, Mass.

During December 1992, we evaluated potential topics for our research effort. As we began to focus our efforts, it became clear that current and future reductions in defense acquisition expenditures would significantly impact how we buy weapon systems. New defense and acquisition strategies are focusing on potentially dangerous regional conflicts, while retaining the capability to respond to emerging threats. Regional powers have increasing access to Western weaponry and high-quality equipment from the former Soviet Union. The United States must maintain its technological advantage to meet this threat.

The Director of Defense Research and Engineering (DDR&E) has formulated a new science and technology (S&T) strategy to address this challenge. The core of this strategy is to provide for early, intensive and continued involvement of warfighters in weapon design; fuel and exploit the information technology explosion; and conduct extensive and realistic technology demonstrations. From an acquisition viewpoint, the concept of virtual prototyping offers tremendous potential. Imagine building prototypes with computers, testing performance in a synthetic battlefield, conducting trade-off evaluations of existing systems vs. modified systems vs. new systems — all before bending any metal. The possibilities and challenges are enormous, which is precisely why we selected the topic.

Readers pressed for time may wish to proceed directly to the Executive Summary where pertinent points and recommendations are summarized. For others, Chapter One explains the objective, methodology, assumptions and background of the report. Chapter Two explains the defense environment and the role of virtual prototypes in the new S&T program. Those familiar with the S&T initiatives may want to go directly to Chapter Three where the entire spectrum of synthetic environments is discussed. Chapter Four examines the application of synthetic environments in the acquisition process. Chapter Five then gives a detailed account

*NOTE: Since this writing, the Under Secretary of Defense (Acquisition) (USD(A)) has changed to Under Secretary of Defense (Acquisition and Technology) (USD(A&T)).

of synthetic environments applications. The summary and conclusions are contained in Chapter Six, the final chapter.

We could not have undertaken a project of this size without the cooperation and contributions of many people. During the writing of this report, we have been thankful for their help. The faculty and staff at Harvard University and the DSMC have been extremely helpful with their insights and encouragement. Others include Lieutenant Colonel Carl Bryant, USAF (Ret.), former Executive Director of Research at DSMC, who served as our mentor and provided helpful advice throughout the research effort. Special thanks to the DSMC faculty, especially Dr. Robert J. Ainsley and Mr. Randy C. Zittel, for their valuable insights on modeling and simulation. This report would not have been possible without the gracious assistance we received from the many individuals in diverse locations involved in defense and commercial business who discussed their applications of virtual prototyping. Many took time from demanding workloads to share their experiences and comment on the future of modeling and simulation.

Our sincere appreciation to Ms. Joan Sable, fellowship program coordinator, who ensured our administrative and logistical requirements were met at DSMC and Harvard, and whose support enabled us to concentrate our attention and energies on the research and writing of this report. We are grateful to the competent and courteous DSMC librarians who assisted us in obtaining the necessary materials to complete our research.

We appreciate the efforts of the DSMC Press staff for their many hours working on this report to ensure its highest quality. Their willingness to allow the use of color photographs, a first at DSMC, is especially appreciated. Thanks to the Visual Arts staff for their work on the graphs, charts, color photographs and cover page as well as their many hours in the layout of this report.

We dedicate this effort to all those we interviewed. May our report be as helpful to you as you were to us.

EXECUTIVE SUMMARY

PURPOSE

We undertook this research project to assess the feasibility of using virtual prototypes in the DOD weapon systems acquisition process. Our goal was to identify and assess the current uses of virtual prototypes by commercial companies, defense contractors and universities. The Defense Science Board and the Defense Modeling and Simulation Office are confident that virtual prototyping can have a beneficial influence on the defense acquisition process. We were skeptical about the usefulness of virtual prototyping and were curious to see who, if anyone, was using virtual prototypes in the development process. We wanted first-hand impressions from people with hands-on experience on how they viewed the utility of virtual prototypes, their successes, disappointments, key risks and challenges. Because "virtual prototype" is becoming a buzzword in today's vernacular, we wanted to know what people from industry, government and academia meant by the term and how they envisioned its application. This then was our charter — to assess and describe the current state of virtual prototyping.

METHODOLOGY

We approached this project from four different directions. While at the Harvard University Graduate School of Business, we discussed our topic with faculty members and with fellow students from U.S. and international companies. A primary reason for pursuing the topic was the emphasis Harvard University placed on the importance of gaining a competitive advantage. The decline of the our nation's manufacturing base reflects the difficulty of competing in today's international markets, so our topic seemed particularly relevant in its exploration of techniques to enhance competitive advantage.

Upon returning to the Defense Systems Management College, an extensive literature review identified more than 500 articles of possible relevance including books, periodicals, research reports, government policy letters, instructions and regulations. Ultimately, we relied directly on more than 150 documents for this report. Our background research indicated that no one, to date, had addressed the broad range of virtual prototype applications nor had any comprehensive assessment of its current and potential benefits to the defense acquisition process been explored. We found the literature on current applications to be limited, and after several visits to contractor facilities we began to understand why. Each company considers virtual prototyping a key ingredient of their ability to compete, and they do not want the specifics of *how* they are using this technology to become available to their competition. We agreed with each company, prior to our on-site visit, not to publish anything they considered to be sensitive and we have honored their requests in this report. This agreement notwithstanding, one of the most beneficial aspects of this report may be our compilation of releasable information on real-world applications.

Comments from real-world practitioners were especially helpful, and the insight they provided could not have been collected without on-site interviews. By visiting several of the leading universities sponsoring research in this field, we were able to observe and operate some of the futuristic equipment that will be influencing this technology during this decade. Our report is a combination of what is being used today as well as a look at what might be used tomorrow. The candor of the people with whom we spoke is greatly appreciated. Accordingly, we believe this study is important because it provides information that is not available elsewhere. It is particularly relevant to today's defense acquisition policy makers as well as those responsible for establishing national policy and programs to enhance our country's infrastructure and our competitive position in the international marketplace.

ASSUMPTIONS

We assume the current defense budget reduction trend will continue for the foreseeable future and DOD will need to be more efficient with its ever-decreasing acquisition budget. Because we assume the future will present even more significant acquisition management challenges to DOD, we believe it is important to examine technology that may enable the defense acquisition process to maximize the nation's warfighting return for its limited investment. If budgets do not dramatically decrease in the future, we believe virtual prototypes can still play a significant role because they have become a key element in maximizing the benefits realized from concurrent engineering programs.

BACKGROUND OF THE PROBLEM

Fundamental changes are underway in the defense acquisition process. The Cold War has ended and the Arms Race has been won. No longer does "The Threat" drive the acquisition process and with its demise goes the funding that permitted multiple major weapon system new starts. The DOD is dramatically refocusing its acquisition philosophy to ensure only weapon systems which significantly influence the outcome of a future battle will be produced. A new system must demonstrate its value-added warfighting capability prior to obtaining approval to expend significant resources on its development and production.

Where and how will this be accomplished? The DOD is creating an *electronic battlefield* that will become the site of future weapon system evaluations. Virtual prototypes will become the means through which the warfighting impact of each existing and proposed system will be assessed. Because the virtual prototype is a key ingredient in this new acquisition philosophy, understanding its heritage and future potential is essential for all participants in the acquisition process.

What then is a virtual prototype? According to the Defense Modeling and Simulation Office, it is "a computer based simulation of a system or subsystem with a degree of functional realism that is comparable to that of a physical prototype." This report explores the world of virtual prototypes.

Chapter One provides an introduction to our study and explains our research methodology. Chapter Two contains an assessment of the changing DOD environment and outlines the recent changes in acquisition policy. Included is a summary of the new Science and Technology Strategy and the Seven Thrusts that are designed to provide focus for the development community.

SPECTRUM OF SYNTHETIC ENVIRONMENTS

In Chapter Three we provide an overview of the synthetic environment, from its foundation to its future. Because realistic and accurate digital representations of each part, component or end product being designed are required, Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) provides the fundamental basis for most virtual prototypes. We discuss current uses of this technology and address the key advances that are being used to create synthetic environments for design and manufacturing. The dramatic increases in computer processing have been exploited by the leading suppliers of CAD/CAM systems, and almost all now have the ability to create three-dimensional drawings that can be rotated for better viewing. Not long after this capability was introduced, enhanced capabilities such as meshing, solid modeling and finite element analysis became available on mainframe computers. Initially these programs resided only with highly-trained specialists working on special applications, but now more robust and easier-to-use software has dramatically changed this situation. The CAD/CAM programs such as Computer-Aided Three Dimensional Interactive Applications (CATIA) and Pro/Engineer have become standard engineering design tools in most of the major design and manufacturing facilities that we visited. New, more powerful workstations have now made it possible for design and manufacturing engineers to have this capability at their desks and the mainframe is now required only for extremely complex or massive projects.

During our on-site visits to contractors throughout the United States, we were able to observe this powerful capability in action. The largest application we witnessed was at the Boeing Aircraft Company where approximately 2,200 workstations and eight of the largest mainframes IBM builds are used to design their newest commercial aircraft, the Boeing 777. Boeing has invested approximately $100 million in this capability because they are convinced it is critical to maintaining the competitive advantages needed for their future success. Based on the high fidelity of their digital design, Boeing has decided *not* to build a physical mock-up and will proceed directly from the digital model to the manufacturing floor. We were able also to observe smaller contractors that have successfully incorporated digital design and manufacturing capabilities similar to those used by Boeing, but on a more limited investment budget. We were extremely impressed, for example, by the excellent results the small engine division of Kohler Corporation has achieved with a relatively modest investment in this technology. Corporate foresight that saw the potential and made the hardware and software investment, coupled with the hard work of its designers and manufacturing personnel, has resulted in Kohler being able to produce and sell one of the best small engines in its class. They have not only been able to survive in a very competitive environment but have actually gained market share at the expense of their Japanese rivals. They attribute much of their success to their digital design capabilities because they now can rapidly evaluate numerous design iterations and optimize them for performance and producibility before building. Eliminating the need for one physical pro-

totype in their design cycle has allowed them to gain a competitive advantage by being able to bring newer/more advanced products to the marketplace in less than half the time it previously required.

We have also included a discussion on the risks associated with the use of these new engineering and manufacturing analysis tools. The collapse of the Hartford Coliseum "space-frame" roof is discussed briefly as a reminder that the majority of all engineering failures result from faulty judgments, not from faulty calculations.

A relatively new innovation called stereolithography takes a digital design created by the CAD/CAM process and uses it to produce a plastic prototype rapidly, either a dimensionally scaled model or a limited-run production sample. These rapid prototypes facilitate the visualization process that supports concurrent engineering by allowing engineers to assess and modify designs better, to meet user requirements and manufacturing capabilities. Stereolithographic parts also make it easier totest accurately for proper fit and interference problems. They can be used to enhance communications with vendors, especially when obtaining quotations for complex parts. Significant savings can be realized also in tooling development through the use of stereolithography. General Motors, for example, is so convinced of this benefit that it has recently decreed that all parts requiring tooling must employ stereolithography.

Probably an even more important use for stereolithography is supporting marketing efforts with potential customers. No longer must the salesman depend on an artist's conception; with stereolithography, the customer can see and feel the new product before starting the manufacturing process. This has been especially useful in reducing the number of design changes that are requested late in the development process and cost inordinate amounts to implement.

Many engineers believe it is no longer necessary to produce a physical prototype because new hardware and software capabilities now permit the creation of a virtual prototype that is even more useful than one created from stereolithography. "I don't need to make a plastic gear; I know what gears look like. I want to see the areas of stress so I can optimize its design, weight, and producibility." Statements like this illustrate the confidence engineers are starting to develop in the use of virtual prototypes and may signal the beginning of a transition away from physical prototypes. As discussed earlier, Boeing made a dramatic corporate commitment to this digital conversion.

Our review of released and draft DOD policies on simulation and modeling indicates virtual prototypes will become a key ingredient in the weapon system evaluation process also. The science and technology (S&T) strategy stresses the importance of virtual prototypes and Thrust Six and Seven specifically address their application to the acquisition process. The Defense Modeling and Simulation Office, Advanced Research Project Agency (ARPA), and the military services are all in the process of expanding their use of virtual prototypes and new and additional policy guidance is expected in the near future.

The "ultimate computer experience" is one way to describe the emerging technology that constitutes the upper end of the spectrum of synthetic environments. Virtual reality is a subject of enormous curiosity to academia, industry, governments and, most of all, the media. Because virtual reality offers so many potential new uses for computer technology and because the entertainment industry has already incorporated many of these features in its latest releases, the term "virtual" has become a key ingredient in attracting public attention. Hardly a day goes by without a newscast or magazine article that announces a new "virtual" something: virtual design, virtual product, virtual corporation or virtual vision. Behind all the flashy titles, however, resides a nascent technology that many experts at the universities and research labs we visited believe has the potential to be one of the single most powerful computer advancements known to man. It has been referred to as the ultimate computer interface because the computer will be operated with natural gestures such as walking around, looking around, and using hands to manipulate digital objects. Dr. Thomas Furness, Director of the Human Interface Technology Laboratory at the University of Washington, believes virtual world, virtual environment and virtual reality are interchangeable terms, and he defines them as: "The representation of a computer model or database in the form of a system of virtual images which creates an interactive environment which can be experienced and/or manipulated by the user." He defines virtual images as visual, auditory and tactile stimuli which are transmitted to the sensory end organs so they appear to originate from within the three-dimensional space surrounding the user. To experience virtual reality today, the participant usually must put on some type of head-mounted display with a position sensor, insert a hand in a data glove, and employ the services of a powerful graphical computer with image-rendering capabilities.

In the virtual reality section of our report, we summarize many of our first-hand experiences with the maturity of hardware and software used to create virtual reality. Most virtual prototypes we have discussed do not meet the academic definition of virtual reality. Immersion and navigation are the two primary characteristics that separate virtual reality from most other types of computer representations. Immersion is the sensation the participant experiences from being surrounded by the digital world or environment. The images are projected in such a manner that the human eye conveys the impression you are inside the scene, not on the outside looking in. Navigation is the ability of the participant to move around inside the digital environment. In the virtual environments we observed at the University of Washington, the participant can "fly" through the sky, swim up to and around as well as "touch" the digital fish, or walk down the streets of a "virtual" city.

We witnessed a much more powerful virtual reality computing capability at the research facility of the University of North Carolina at Chapel Hill. This facility is concentrating on developing a powerful computer processing capability to support higher-resolution image generation. The Pixel-Planes 5 multicomputer system they have developed has the highest quality graphics of any location we visited. The computer-generated digital topography scene, for example, looked exactly like a photograph taken with a high-powered lens. It was especially impressive because the digital images had not been scanned in originally.

In the final section of this chapter, we discuss modeling and simulation and the issues facing the DOD simulation community. We provide a technology assessment, and briefly describe two ARPA programs that are using current technology to implement virtual prototypes in DOD simulations.

Modeling and simulation are related but not interchangeable. Modeling is the development of equations, constraints and logic rules, while simulation is the exercising of models over time. Simulation contains models but models do not contain simulations. Informal DOD papers have separated simulation into three categories: constructive, virtual and live. A brief description of each is provided below.

CONSTRUCTIVE: Wargames, models and analytic tools developed by the individual Services.

VIRTUAL: Systems simulated both physically and by computer. Real people fight on synthetic battlefields, interacting with each other and with artifacts in the simulation. Examples include individual aircraft simulators, tank simulators and virtual prototypes.

LIVE: Operations with live forces and real equipment in the air, on the ground, on and below the sea. Also included in this category are hardware prototypes on instrumented ranges. Examples include exercises such as REFORGER and training rotations at the National Training Center.

Future DOD acquisition evaluations will probably utilize one or more of these simulation categories and most major weapon system acquisitions will be accomplished usually by utilizing a combination of all categories in the requirements definition, development, production, training, and operational phases of the program.

The Simulation Networking (SIMNET) Project is a joint Army and ARPA project that uses distributed simulation as both a prototype training device and a new technology testbed. The ARPA has used this program as a vehicle to demonstrate new technology associated with a distributed simulation architecture. The SIMNET has evolved from a training device to a means for evaluating acquisition alternatives and, as such, is the genesis for DOD's new simulation initiatives. Battlefield Distributed Simulation-Development (BDS-D) is a follow-on development network based on the success of SIMNET. It will focus on providing a warfighting assessment capability network using a soldier-in-the-loop virtual reality approach. The BDS-D will address the issues of verification, validation and accreditation of distributed interactive simulation models, as well as DOD and industry standards and protocols that are used for the distributed interactive simulation architecture.

SYNTHETIC ENVIRONMENTS IN ACQUISITION

In Chapter Four, we review briefly the DOD acquisition process for the benefit of readers who may not be familiar with the milestone approach to acquisition. Selected DOD acquisition policies "Translating Operational Needs into Stable, Affordable Programs" and "Acquiring Quality

Products" are described to provide a basis for discussing what we believe are functional areas where the acquisition community may benefit from the expanded use of virtual prototypes in the acquisition process.

The DODD 5000.1 requires a Mission Need Statement (MNS) to be expressed by the user community in broad operational capability terms. The steps involved in the MNS approval process and the actions required to obtain a Milestone I (New Start) decision are illustrated and discussed. Also in this section is a brief discussion of DOD guidance on acquisition strategies, exit criteria and risk management. At the New Start milestone decision, broad objectives for cost, schedule and performance parameters are established. These parameters are reviewed and refined at each subsequent milestone review and provide the basis for program baselines. The balance of this chapter discusses functional areas associated with the acquisition process and the potential benefits that each might derive from the use of virtual prototypes. The five functional areas are: analysis, research and development, testing and evaluation, production and logistics, and training.

In the analysis area, virtual prototypes can be used to conduct electronic battlefield evaluations that will assist in determining the type and number of weapon systems required to support military participation in future conflicts. Weapon system analysis can be expanded to assist in the force structure analysis associated with the maintenance and transportation requirements necessary to support these new warfighting systems. Because virtual prototypes are digital, they can provide excellent support to configuration analysis and cost analysis activities. Tradeoff studies and sensitivity analysis can benefit from this new technology because it can support the evaluation of multiple configurations as well as permit the performance assessments to be conducted in a controlled and repeatable environment. Campaign analysis can benefit from modeling and simulation, but we do not believe it will receive any significant benefits from the use of virtual prototypes. This assessment is based on the fact that it is not currently practical or cost-effective to involve hundreds or thousands of man-the-loop virtual prototypes in the extended analysis that would be required for a campaign simulation. Virtual prototypes can be extremely beneficial in achieving system advocacy because they support the "visualization" of the new system. Program managers will now be able to have the ultimate marketing tool, a computer-based animated model of their system that they can carry with them and demonstrate whenever the opportunity presents itself.

The benefits to be derived from the use of virtual prototypes in the research and development area are extensive. Early visualization of the product to be produced greatly assists the user in defining his requirements accurately and helps communication between the developer and the user communities. Because the virtual prototype is normally refined through the use of CAD/CAM data, it provides an excellent means to maximize the productivity of each member on an integrated product development team. Functional representatives are able to understand better the concerns and needs of their counterparts at a very early stage in the design process. Because historical data has shown that more than 80 percent of the total cost of a system is determined by decisions made prior to the Engineering and Manufacturing Development phase,

optimizing these critical decisions is extremely important. The test and evaluation community can benefit also from the use of virtual prototypes because they can be used to obtain early operational assessments of the system. The user can *operate* the virtual prototype for a stand-alone assessment, and it can be *connected* to the electronic battlefield for warfighting evaluations.

As mentioned under research and development benefits, obtaining early assessments of a design is extremely valuable because such a large part of the total cost is determined during the initial phases of a product development. Developmental and operational testing can also benefit from the use of virtual prototypes. By using a virtual prototype, the tester can optimize his test scenario and data collection to support milestone decisions. It should be easier for the test community to collect various types of performance data using a virtual prototype because it is digital and thus easier to instrument. In many programs, it may be possible to eliminate the need for a physical prototype to support testing. Boeing Aircraft Company, for example, is building their new Boeing 777 aircraft directly from their digital model, no physical mock-ups will be built. They also are using their digital design information with specialized analysis software to perform extensive structural and electrical evaluations. They believe they can use these results to build a deliverable product that will have a high probability of passing all the technical and operational tests.

Production and logistics can benefit from the use of virtual prototypes because the digital designs for the individual parts have been optimized for producibility via use of CAD/CAM software. Tooling design can be started also at an early stage through use of the virtual prototypes digital information and visualization capabilities. Concurrent engineering can benefit from virtual prototypes because they provide a means to see the product that is being designed. Visualization has proven to be a powerful medium that dramatically improves the communication between concurrent engineering functional team members. Logistics will benefit from the use of virtual prototypes because they allow maintenance requirements to be evaluated early in the design process. Boeing and Sikorsky have used virtual prototypes to enhance their design for subsequent maintainability by having maintenance personnel *perform* typical maintenance operations on their virtual prototype and provide feedback to the designers prior to freezing the design.

The benefits virtual prototypes can offer to training are almost unlimited. Simulators were developed specifically for training, and have been extremely valuable in optimizing the benefits received for each training dollar spent. High-fidelity trainee-in-the-loop simulations that involve virtual prototypes will be the primary training mechanism in the future, especially if funding for real-world training exercises continues to be reduced. Because the benefits of simulation are so well documented and accepted, we did not conduct specific research in the use of virtual prototypes in this area. Additional research should be conducted in the use of virtual prototypes in general education.

EXAMPLES OF SYNTHETIC ENVIRONMENTS

In Chapter Five we provide an overview of our visits to industry, government and academic facilities that are developing or utilizing virtual prototypes. This portion of our report constitutes the primary database from which our comments/assessments in earlier sections have been drawn. We have been extremely fortunate in the cooperation we have received while conducting this research. Candor and the willingness to share real-world experiences with us are two attributes that characterize best each of our face-to-face interviews with personnel involved in the use of virtual prototypes. We have included information from our on-site observations at Boeing, General Dynamics Electric Boat Division, Sikorsky, Kohler, ARPA, NASA/Ames, University of North Carolina (Chapel Hill), University of Washington Human Interface Technology Laboratory, and the U.S. Army Night Vision and Electronic Sensors Directorate. Based on our first-hand observations, virtual prototypes are being used in everything from the design and manufacture of lawnmower engines to the design, marketing, test and manufacture of the world's most sophisticated aircraft. If you have any doubts about the potential uses and benefits of virtual prototypes, please read our discussion on Boeing or Sikorsky.

CONCLUSIONS AND RECOMMENDATIONS

In the final chapter of our report we set forth our conclusions on the status of virtual prototypes and make recommendations that address acquisition policy, program managers and industry. Our conclusions and recommendations are presented in a summarized fashion below.

Conclusions

1. Virtual prototypes can eliminate the need for some and, in certain specific cases, all physical prototypes.

2. Simulation still contains risks that should not be overlooked.

3. Rapid prototyping techniques can greatly accelerate the production of new commodities.

4. Virtual prototyping can provide a clear, competitive edge to companies who embrace and successfully implement its features.

5. Virtual reality has great potential, but it is not clear when DOD will be able to benefit from the use of this emerging technology.

6. Verification, validation and accreditation of synthetic battlefields and virtual weapon systems is a major challenge, and substantial investment will be required to enhance our current capability in this area.

7. Computing power available today falls short of that needed to produce high-quality images for synthetic environments, and implementing a desirable level of realism will require a significant investment in the development of hardware and software.

8. Virtual prototypes can be a valuable management tool for program managers to use in identifying and managing program risks.

9. Major weapon system acquisition decisions in the near future will be influenced significantly by the performance of virtual prototypeson synthetic battlefields.

10. A virtual prototype can be a positive influence program support at all levels of the DOD acquisition process.

11. Virtual prototypes can help the contractor and government program manager understand new doctrinal concepts and the warfighting impact of new systems by providing a means for the designers to visualize and interact with their product.

12. Virtual prototypes can provide developmental and operational testers with the ability to conduct meaningful evaluations and can aid in the design of tests performed during each phase of an acquisition.

13. Concurrent engineering can result in products which incorporate state-of-the-art technology and satisfy customer needs and manufacturing capabilities.

14. Successful implementation of virtual prototyping requires a significant commitment from senior management because the implementation and utilization process involves a major cultural change for the organization.

15. The modeling and simulation infrastructure within DOD needs to be improved.

16. If distributed interactive simulation is used to make acquisition decisions, the elements of the simulation network need to provide an environment sufficiently accurate so results can be used with confidence.

17. The understanding of weapon systems and processes gained by using virtual prototypes will enhance the fundamental understanding of systems, subsystems and manufacturing processes and make it easier to optimize designs for performance, producibility and reliability.

Recommendations

Acquisition Policy

1. Virtual prototypes should be encouraged in lieu of physical prototypes whenever possible, and dual-use funding should be targeted to this area.

2. Virtual reality has great potential, but when DOD will benefit from this technology is not clear. Virtual reality research should be continued.

3. An organization needs to be established with the responsibility for establishing standards and common tools for verification, validation and accreditation of all synthetic environments.

4. Rapid prototyping tools and techniques greatly accelerate the development of new products and should be required in contracts for parts and subsystems wherever possible. The use of stereolithography and other similar technologies should be encouraged.

5. Software development tools which support the rapid construction of battlefield simulations need to be developed. They must look real and must present the same conditions to all participants. The environments must provide semiautomated forces which mimic human behavior. Finally, these models of realistic human performance and decision-making need to be validated.

6. Incorporate virtual prototypes in developmental and operational test plans as a substitute for physical prototypes wherever possible and use them to aid in the design of the tests that will be performed during each phase of an acquisition.

7. Establish a modeling and simulation infrastructure responsible for data communication standards and tools which do not exist today.

8. The distributed interactive simulation environment must be validated and verified to ensure that it is sufficiently accurate so simulation results can be used with confidence.

Program Managers

1. Virtual prototypes are a powerful tool for managing program risk. Virtual prototypes should be used to measure performance against milestone decision criteria. They can be used to test the system or certain high-risk subsystems against certain simulated threats, to assess the effectiveness of the technology and to evaluate the feasibility of the design for producibility.

2. Virtual prototypes are useful in obtaining and maintaining system support. They can have a positive influence on product support at all levels of the acquisition process. Use them to demonstrate the "value-added" capabilities of your system while at the same time convincing the audience that the technical and financial risks associated with obtaining this capability are reasonable. Virtual prototypes can be used also to increase user involvement in the development process by providing a better foundation for user and developer communications.

3. Plan to have your system tested in a simulated battlefield early on. Find out your system's strengths (warfighting value-added characteristics) to support your program advocacy activities and identify potential weaknesses so they can be corrected as soon as possible.

4. Virtual prototyping activities support the DOD dual-use efforts. Ask to formally participate in this program and seek additional funds to support your participation.

Industry

1. Virtual prototyping provides a clear competitive edge to companies who embrace and implement it successfully. Encourage and support its use at every opportunity.

2. Concurrent engineering is an absolute requirement for competitiveness in the 1990s. Virtual prototyping will facilitate the adoption of this concept.

3. Senior management support is required for implementation of successful virtual prototyping. The conversion to digital design concepts will involve a major cultural change, and a significant transition period should be allowed prior to mandatory conversion.

While theoretically and technically television may be feasible, commercially and financially I consider it an impossibility, a development of which we need waste little time dreaming.
— Lee DeForest, Physicist
1926

Chapter 1
INTRODUCTION

We undertook this research project to assess the feasibility of using virtual prototypes in the weapon systems acquisition process. Our goal was to identify and assess current applications of virtual prototyping by commercial companies, defense contractors and universities. The Defense Science Board and the Defense Modeling and Simulation Office are confident that virtual prototyping can significantly influence acquisition in the future. We were skeptical about the usefulness of virtual prototyping and curious to see who, if anyone, was using virtual prototyping as an aid in design, manufacturing and testing of commercial or defense systems and to examine their experience with virtual prototyping. We also wanted to know what meaning people from various industries and backgrounds give to the term virtual prototype and what one can realistically expect its usefulness to be. We were interested in identifying the key risks and challenges associated with virtual prototyping. Our charter, then, was to assess and describe the current state of virtual prototyping.

METHODOLOGY

We approached this project from four directions. First, while at the Harvard Business School, we discussed with faculty members and associates from commercial sectors our topic and its relevance in today's business environment. A primary reason for pursuing the topic was the emphasis Harvard placed on competitive advantage. Case studies of commercial products emphasized the importance of achieving this advantage. The recent decline of our nation's manufacturing base reflects the difficulty of competing in today's international markets; thus, the exploration of techniques to enhance competitive advantage seemed particularly relevant.

Second, we conducted an extensive literature review that identified more than 500 articles of possible relevance including books, periodicals, research reports, government policy letters, instructions and regulations. We used these to identify documents containing information pertinent to our research effort. Ultimately, we relied directly on more than 150 documents for this report.

Our background research on virtual prototypes indicated that, to date, no one had conducted research which addressed a broad range of applications and the implications of virtual prototypes on the defense acquisition process. Information on current applications is extremely limited. While a great deal of data exists on the potentials of virtual proto-

typing, virtual reality and synthetic environments, there is little concrete information on what has been accomplished. The most beneficial aspect of this report, therefore, may be the compilation of information on significant applications of virtual prototyping. Comments from practitioners were especially helpful and could not have been collected without the on-site interviews that are the basis for much of the information in this report. Accordingly, this study is important because the information collected is not available elsewhere and also because it is particularly relevant to today's defense acquisition policy makers.

Third, we developed a survey form as a guide to collecting information from the more than 50 individuals we interviewed for the project. Our objective was to identify and assess applications of virtual prototyping; however, we soon realized the survey was overly restrictive in situations like at The Boeing Aircraft Company, Sikorsky and The Kohler Company, where virtual prototyping is being used extensively, and too accommodating for companies with little or no experience. Accordingly, we used the survey as a guide to ensure we addressed all the relevant points in our interviews, but not as the basis from which statistical analysis would be performed.

Finally, we conducted more than 50 interviews, lasting from several hours to several days with individuals from academia, government and commercial sectors involved in modeling, simulation, or virtual reality and virtual prototyping. We spoke with senior research scientists, senior acquisition officials, senior vice presidents, program managers and design and manufacturing engineers. We collected as much information as possible from these individuals on their experiences, good and bad, with simulation. We asked numerous questions, listened, and learned a great deal about this new design and manufacturing process. We witnessed numerous demonstrations of the latest tools and technologies, and by wearing head-mounted displays we were able to experience firsthand the new world of virtual reality.

ASSUMPTIONS

We have assumed the decreasing defense budget trend will continue for the foreseeable future. Indications are that the defense budget will come under ever-increasing pressures as Congress and the President attempt to decrease the national budget deficit, while at the same time increasing expenditures on social and health care programs. Virtual prototypes facilitate the integration of design and manufacturing personnel to ensure engineering designs are producible. Because this capability supports a rapid transition to production, it could prove beneficial to the industrial base should world events force us to once again man the ramparts with men and equipment. This is especially true if significant reductions to our defense manufacturing capability continue. Because DOD must maintain its technical superiority so it can defend the nation with a dramatically decreased military structure, maximum return for every dollar invested in research and development is essential. We believe virtual prototypes are vital to this effort.

PROBLEM BACKGROUND

Fundamental changes are taking place in the defense acquisition process. Resource constraints, rapidly expanding commercial computer capabilities and a new acquisition strategy that expands the use of technology demonstrations have dramatically increased the importance of synthetic environments, or simulations, in the acquisition of new weapon systems. Virtual prototypes are a key component of this environment and provide simulations with a high degree of realism. What is a virtual prototype? According to the Defense Modeling and Simulation Office, it is "a com-

puter-based simulation of a system or subsystem with a degree of functional realism that is comparable to that of a physical prototype."

This report explores the world of virtual prototypes. It identifies and discusses current applications of virtual prototypes in the commercial marketplace, defense industry and in university research centers. Our research assesses the implications of synthetic environments on the acquisition process by evaluating the functional areas involved in each step of the process. It concludes with recommendations on how the DOD acquisition process can be improved and how program managers can use virtual prototypes to manage their programs. It also identifies the challenges associated with full implementation of virtual prototypes. Our approach is descriptive in nature and makes maximum use of charts, diagrams and photographs. Appendix D contains a glossary of terms commonly used in describing computer-based simulations to aid readers new to this revolutionary world of simulation.

We must not be misled to our own detriment
to assume that the untried machine can displace
the proved and tried horse.

— MG John K. Herr, USA
1938

Chapter 2

BACKGROUND

Once upon a time, that there was an enemy was basis for an ever-increasing need to develop and field the world's best military hardware. The acquisition process was relatively straightforward in that the user community identified a "need" for a certain capability, based on the assessment of the enemy's current and projected capabilities. The DOD weapon systems acquisition community, government and industry acted immediately to produce a system to fulfill the need. The enemy responded by enhancing its capability through real and imaginary developments. This caused the DOD user to realize the current or near-future capability was no longer sufficient. New threats generated new needs which became new acquisitions, and the circular process evolved into the structured DOD acquisition process of the Cold War era.

Then the unthinkable happened! The enemy decided it didn't want to play this game anymore. Who could have possibly predicted the international events of the last four years? Democratic movements, coupled with the continuing failures of communist-based regimes to fulfill the economic and political needs of their constituents, led to the collapse of the Warsaw Pact. The infamous Berlin Wall was shattered and the small concrete pieces became best sellers in gift shops throughout the world. Once the Warsaw Pact collapsed, the Soviet Union began to unravel, finally disintegrating in December 1991. New "independent" states have emerged in its place and each has its own agenda. Some want weapons of war and some do not. All, however, want to determine their own future and will no longer submit to the desires of the Communist party.

Not long after the Wall collapsed, the world's stability was threatened by the Iraqi invasion of Kuwait. A worldwide coalition came together under U.S. leadership and through use of combined military forces restored Kuwait independence. This historic event was a milestone in international cooperation and, as such, has established the framework for future coalition efforts. The shifts in the strategic environment have been momentous as well as fundamental. Strategic nuclear forces are being reduced and all tactical nuclear weapons have been removed from U.S. ships at sea. The U.S. Army is a nonnuclear force and all ground-launched battlefield nuclear weapons are being eliminated. The Secretary of Defense in his 1993 Annual Report to the President and the Congress stated the following:

Today the United States and its allies are more secure, and the promise of democracy is more real, than at any time in recent memory. America owes its

> *armed forces and their families a debt of gratitude for that achievement. Their service and dedication have been the backbone of this nation's freedom throughout the long years of Cold War and into the new era. America's military strength remains essential as we face the uncertainties and challenges that lie ahead.*

He indicated, also, that the world is still a dangerous place. Although we no longer face the threat of a global war beginning in the Fulda Gap, we do face the possibility of serious regional conflicts. They may be triggered by one or more events, often hard to identify in advance, and possibly extremely difficult to diffuse due to the spread of high-technology weapons. Nuclear, chemical and biological weapons which can be combined with long-range ballistic missiles exacerbate the dangers that can be associated with the regional conflicts of the future.

DOD STRATEGY/FORCE STRUCTURE

The DOD has developed a comprehensive new security strategy to deal with this new environment. It is designed to meet the near-term challenges of regional conflict while simultaneously building the foundation for long-term security in a constantly changing global environment. The following quotation from the Secretary of Defense Annual Report provides the reader with an overview of how this strategy will impact the military.

> *Today it is providing the guidance to refocus defense resources and restructure the military for a new and different security environment. We have used the new strategy as a foundation to plan deep but carefully focused reductions in our force structure. The goal is a smaller but still capable force that preserves essential combat capability.*[1]

DOD MANAGEMENT AND ACQUISITION STRATEGY

Reform efforts are underway in DOD to consolidate financial accounting, corporate information management and other common functions and apply efficient business practices to reduce costs. This increased efficiency should permit future DOD budgets to focus on training, support and the development of advanced weapon systems. A new strategic approach has also been applied to DOD acquisitions. Procedures governing acquisitions are being simplified and an increased focus has been placed on technology research and development. The production of weapon systems, both type and number, is being dramatically reduced since near-term threats are considered small when compared to ours and our allies' combined capabilities. Inherent in this revised acquisition strategy is the recognized need to maintain the technological advantage that provides the decisive edge in any future conflict.[2]

DOD BUDGET

Our enemy, the basis for our acquisition process, has all but disappeared. Without the Joint Chiefs of Staff validated "threat" to provide the basis for new acquisitions, the DOD in the mid-to-late 1990s will be vulnerable to the competing needs of other government agencies. Current congressional budget debates vividly reflect the demise of the Soviet threat and, as expected, DOD downsizing is viewed as the source of funding for new social initiatives. The estimated $259.1 billion in DOD fiscal year (FY) 1993 budget authority is 31 percent below FY 1985, as shown in Table 1, and the Secretary of Defense has projected a FY 1994 budget that will be significantly ($12.9 billion) lower than President George Bush's administration requested. In FY 1993, the DOD budget is less than the interest payments on the federal debt and by 1997, defense outlays will fall below three and one-half percent of the Gross National Prod-

Table 1
Declining DOD Budget (Dollars in billions)

Growth Year	Current Dollars	Constant Dollars	Real Growth Percentage
1985	286.8	375.6	-
1986	281.4	359.1	-4.4
1987	279.5	245.7	-3.8
1988	283.8	338.5	-2.1
1989	290.8	333.7	-1.4
1990*	291.0	423.1	-2.9
1991*	276.0	292.9	-9.6
1992*	274.5	284.7	-2.8
1993	259.1	259.1	-9.0
FY 1985-93 real change:			-31.0

*Excludes costs of Operations DESERT SHIELD/STORM.

uct (GNP) and become the lowest since before Pearl Harbor.[3]

The DOD is attempting to link its outyear budgets with its long-term strategy. The overall goal of the current budget plan is to properly fund the new regional strategy originally announced by President Bush and subsequently adopted, in concept at least, by the Clinton administration. As new and larger demands are placed on the Secretary of Defense to give up even more funding in the outyear budgets, the difficulties associated with adequately funding this new post-Cold War regional strategy will continue to escalate. Figure 1 illustrates the downward trend we are experiencing and most discussions on Capitol Hill are not about regional conflicts but about *more* DOD budget reduction and *how quickly* it can be accomplished. This discussion is not meant to imply "the sky is falling," only that the nation can no longer afford to buy large quantities of the latest and greatest protection systems. The projected FY 1994 budget of $250.7 billion is still a significant commitment by the nation to fund the DOD, but achieving an adequate level of security with reduced funds will require a new streamlined infrastructure and a new approach to the acquisition of future weapon systems.

Because the threat has been significantly reduced, DOD is not under pressure to modernize the fighting capabilities of its forces rapidly. Concurrency in development programs will be reduced dramatically to mitigate risk and cost impacts, and equipment currently in the field will be retained for much longer periods of time. Faced with a considerably smaller budget in the future and with the potential for new threats to emerge, DOD has implemented a new and revitalized Science and Technology (S&T) program to:

> *...develop and make available to the military forces new, advanced and affordable technologies that will ensure long-term military superiority. ...This strategy will seek to sustain and apply the dramatic advances in information technology, involve the military user early and continuously, and demonstrate technology as extensively and realistically as possible.*[4]

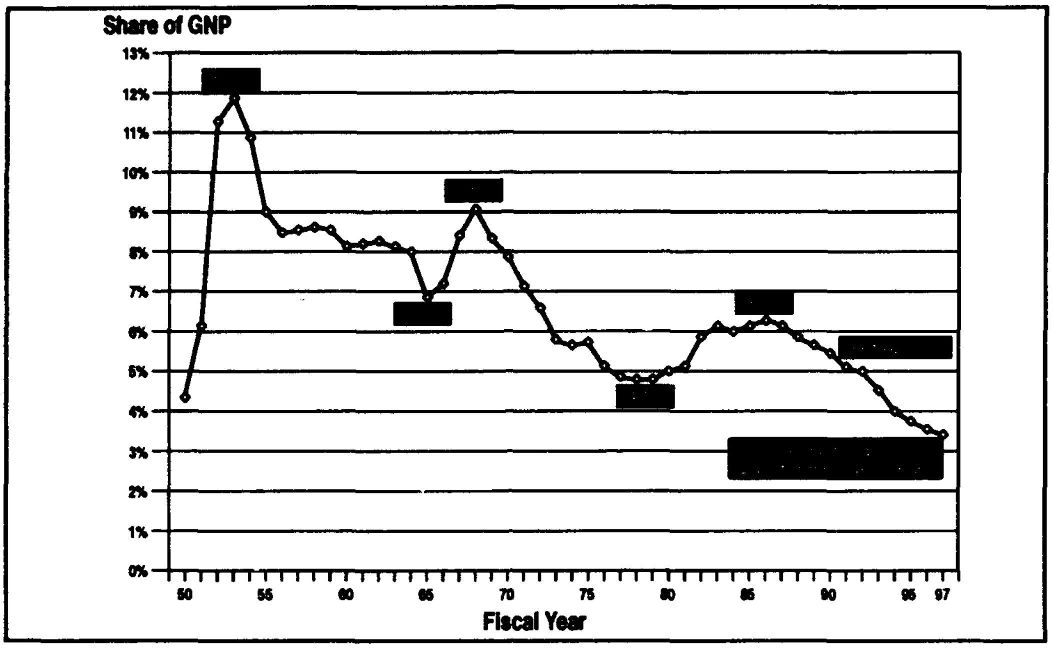


Figure 1. **Defense Outlays as a Share of GNP (Source: 1992 Joint Military Agreement)**

SCIENCE AND TECHNOLOGY PROGRAM

The Director of Defense Research and Engineering (DDR&E) is responsible for the Science and Technology (S&T) program within the DOD. In July 1992, DDR&E released the first comprehensive post-Cold War S&T strategy to provide a blueprint for technology development and resource allocation in the 1990s. The strategy stresses the importance of feedback from the warfighters in providing concepts, doctrines and military needs to the developers of technology and systems. It also stresses the "feed-forward" of new technology and systems from the developers to the operators.[5]

This process will be implemented electronically and will involve a dramatically expanded and integrated set of instrumented training ranges and electronic battlefields. Networked "synthetic environments" provide the foundation for bringing developers, scientists, engineers, manufacturers, and warfighters together to accomplish the goal of "early, intensive and continued involvement of warfighters."[6]

A second key facet of the new strategy is to revolutionize military operations by taking advantage of the rapidly expanding capabilities in information technology, both hardware and software. The exponential increase in computer performance and increasingly more capable computer networks have fueled this information technology explosion, and similar performance trends are expected to continue. As a result, enormous opportunities exist to design more capable and affordable military systems, to train the force better and to create more effective command, control, communications and intelligence (C^3I) structures. Military user involvement in the development process will be enhanced

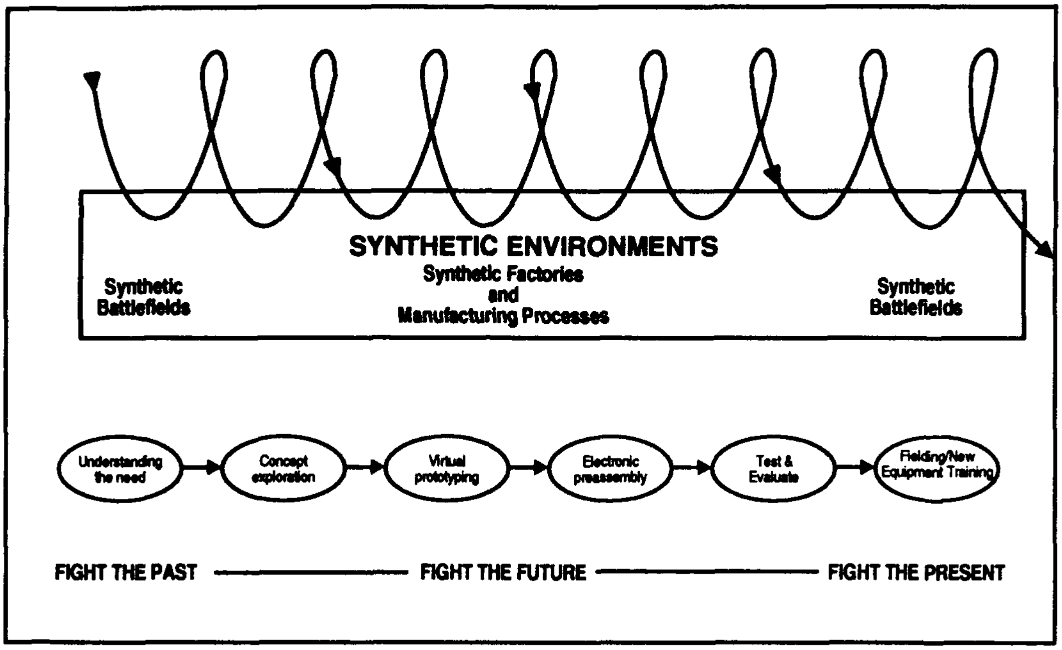


Figure 2. **The New S&T Strategy: Involvement of Warfighters**

dramatically by the technology revolution as it will permit using more realistic and interactive simulations and exercises to evaluate emerging technologies without expending substantial resources. Figure 2 shows the process envisioned to permit maximum involvement of the warfighter.[7]

To ensure the technology is ready, manufacturing processes are available, and operating concepts are understood before a formal acquisition program is undertaken, the DDR&E will sponsor Advanced Technology Demonstrations (ATD) to validate specific capabilities. Technology demonstrations are not new to the acquisition process. What is new is the scope and depth of the envisioned ATDs and the central position they will play in the acquisition process. "These demonstrations of capability, coupled with advanced simulation techniques, will lead to comprehensive assessments of technical feasibility, affordability, and operational utility," according to DDR&E S&T strategy.[8] In simplistic terms, the developer of a new weapon system must *demonstrate* the operational benefits or, in business terms, the "value added" of his concept in influencing the outcome of the battle. The "battle" in this case will be conducted on an electronic battlefield controlled by the DOD acquisition community (developers, testers, users, etc.) Figure 3, on the following page, graphically portrays the three key tenets of the S&T strategy and their interactions.

PROVIDING FOCUS - SEVEN S&T THRUSTS

To ensure the S&T program is properly focused in the development community, seven "Thrusts" have been established by the DDR&E. Quoting from the S&T Strategy:

> *Seven Thrusts have been defined to represent the demands being placed on the S&T program by the user's most pressing military and operational require-*

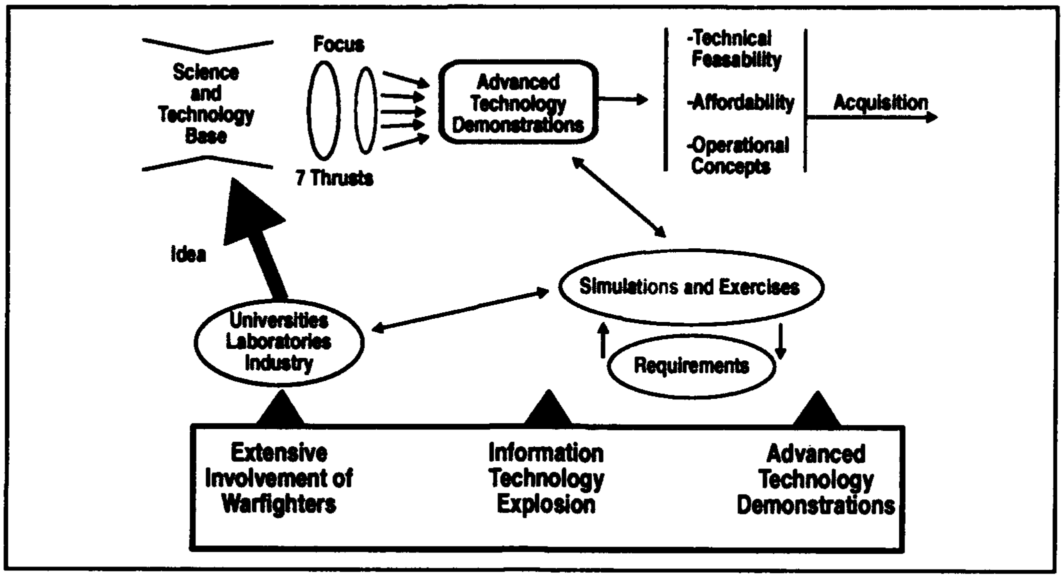


Figure 3. The New S&T Strategy

ments. While there are goals and activities in the S&T program that fall outside of these Thrusts, it is crucial to the success of the S&T program that investments be focused on those efforts which show the greatest promise for improving future military capabilities, rather than simply providing a "balance" across all possible options. Focus, not balance, is the watchword of the new S&T strategy.[9]

The following paragraphs briefly describe the seven Thrusts as stated in the S&T strategy report.

Global Surveillance and Communications. The ability to project power requires a global surveillance and communications capability that can focus on a trouble spot, surge in capacity when needed and respond to the needs of the commander.

Precision Strike. The desire for reduced casualties, economy of force and fewer weapons platforms demands that we locate high-value, time-sensitive fixed and mobile targets and destroy them with a high degree of confidence within tactically useful timelines.

Air Superiority and Defense. The need to defend deployed military forces, and help defend allies and coalition partners, from the growing threat of high performance aircraft and ballistic and cruise missiles, and the need to maintain decisive capabilities in air combat, interdiction and close air support, require a strong effort in missile defense and air superiority.

Sea Control and Undersea Superiority. The ability to maintain overseas presence, conduct forcible entry and naval interdiction operations and operate in littoral zones, while keeping loses to a minimum, presupposes a strong capability in sea control and undersea warfare.

Advanced Land Combat. The ability to rapidly deploy our ground forces to a region, ex-

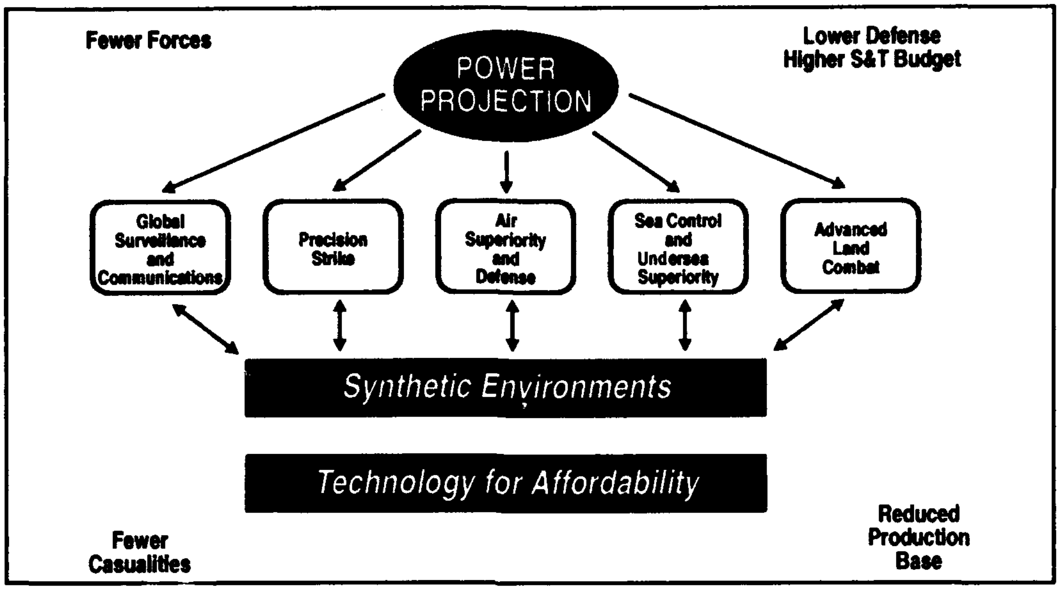


Figure 4. **The New S&T Strategy: the Seven S&T Thrusts**

ercise a high degree of tactical mobility and overwhelm the enemy quickly and with minimal casualties in the presence of a heavy armored threat and smart weaponry requires highly capable land combat systems.

Synthetic Environments. A broad range of information and human interaction technologies must be developed to synthesize present and future battlefields. We must, therefore, synthesize factory-to-battlefield environments with a mix of real and simulated objects and make them accessible from widely dispersed locations. Integrated teams of users, developers, and/or testers will be able to interact effectively. Synthetic environments will prepare our leaders and forces for war and will go with them to the real battlefield.

Technology for Affordability. Technologies that reduce unit and life cycle costs are essential to achieving significant performance and affordability improvements. Manufacturing process and product performance issues are integral parts of the program. Advances are particularly needed in technologies to support integrated product and process design, flexible manufacturing systems that decouple cost from volume, enterprise-wide information systems that improve program control and reduce overhead costs, and integrated software engineering environments.

Figure 4 shows the relationship of the Thrusts to the overall DOD acquisition environment. Inherent in this illustration of the seven Thrusts in the S&T strategy is the concept of utilizing emerging technology (Synthetic Environments and Technology for Affordability) to enhance the ability of the other five Thrusts to achieve their goals. As illustrated, "Involvement of Warfighters" is facilitated by using "Virtual Prototypes" in a "Synthetic Environment." The virtual prototype enables the user to better define his system requirements in the acquisition evolution, and it provides a means for "value added" assessments by DOD decision makers. A similar iterative chart could be drawn depicting the use of virtual prototypes in the engineering design

process within a specific commercial company. "Virtual Prototype," unfortunately, does not have a universally accepted definition and may mean significantly different things to different people. For some people, it may be a simple computer representation of a part, subsystem or end product. For others, a computer-generated prototype must include the ability of the operator to be "immersed" as well as navigate within the model before it is considered a "virtual" prototype. For the purpose of this paper, a virtual prototype is defined as a computer-based simulation of a system or subsystem with a degree of functional realism that is comparable to that of a physical prototype. This definition is in use by the Defense Modeling and Simulation Office.

DEFENSE MODELING AND SIMULATION OFFICE (DMSO)

In 1991, Congress directed the DOD to establish an office to coordinate a Department-wide approach to simulation and training. Mr. Donald J. Atwood, Jr., Deputy Secretary of Defense, responded by undertaking "a new initiative to promote the effective and efficient use of modeling and simulation (M&S) in joint education and training, research and development, test and evaluation, and operations and cost analysis."[10] The DOD Modeling and Simulation Management Plan calls for a DOD Executive Council for Models and Simulations (EXCIMS) to advise the Under Secretary of Defense (Acquisition) (USD(A)) on M&S policy, initiatives, standards and investments. The DMSO serves as the executive secretary to the EXCIMS.[11]

A draft DOD Directive 5000.GG, currently in staffing, is expected to formally establish policy and assign roles and responsibilities for DOD M&S management. Figure 5 shows how the management structure might be defined. The EXCIMS membership, composed of general and flag officers and civilians of equivalent rank, is anticipated to include the following organizations:[12]

— Deputy Director, Defense Research and Engineering (DDDR&E)

— Assistant Secretary of Defense for Command, Control, Communications and Intelligence (ASD(C^3I))

— Assistant Secretary of Defense for Force Management and Personnel (ASD(FM&P))

— Assistant Secretary of Defense for Program Analysis and Evaluation (ASD(PA&E))

— Assistant Secretary of Defense for Production and Logistics (ASD(P&L))

— Chairman, Joint Chiefs of Staff (CJCS)

— Army

— Navy

— Air Force

— Marine Corps.

The DMSO was created to enhance readiness by making better use of limited M&S resources, to identify the organizations responsible for specific M&S activities and to develop a strategy to improve DOD capabilities through M&S. The DMSO has been tasked to establish a DOD-wide structure to coordinate joint M&S activities, develop an M&S master plan and furnish guidance for Component M&S plans, and focus on interoperability and standards by developing common tools and methods. The scope of the DMSO responsibilities, as outlined in the M&S Management Plan, includes:

— Promulgating policies at the direction of the USD(A) that facilitate the application of

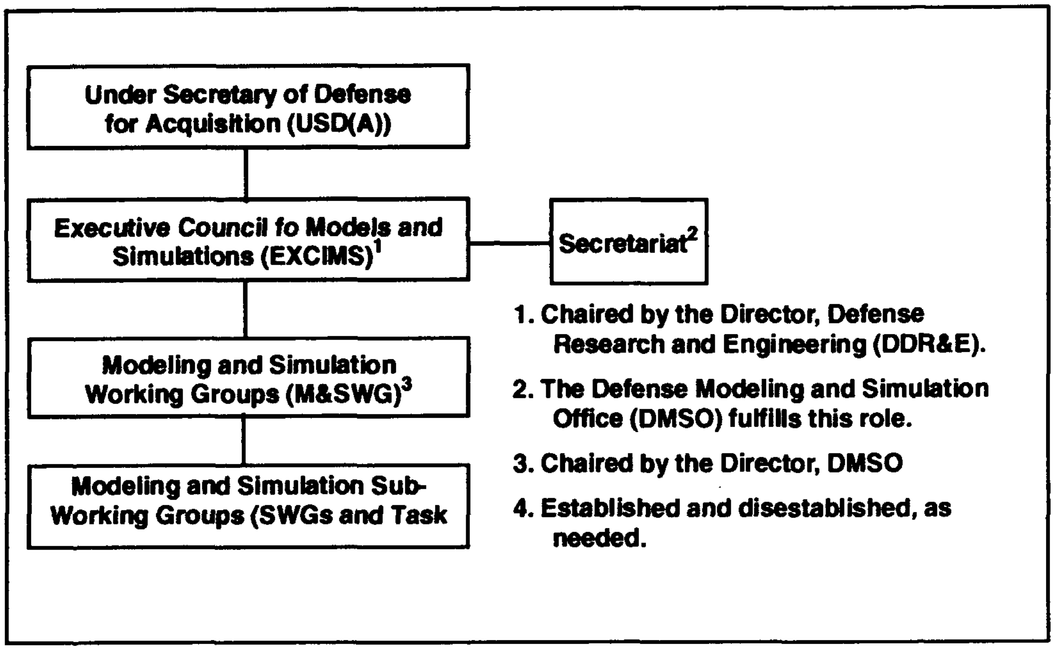


Figure 5. **DOD Modeling and Simulation Management Structure**

M&S among joint education and training, research and development, test and evaluation, and operations and cost analysis disciplines.

— Distributing USD(A) approved guidelines to assist in Component development of consistent M&S plans in configuration management, verification, validation, accreditation and releasability.

— Developing USD(A) approved liaison process to coordinate and assist in the development, acquisition and sharing of M&S technology, standards, verification, validation and accreditation processes among DOD Components and the defense industry.

— Developing USD(A) approved mechanisms to foster cooperation among DOD Components to maximize M&S interoperability while eliminating duplicative development of M&S advanced technologies.

— Advising the USD(A) on matters relating to improving the use of M&S that supports input to the Joint Requirements Oversight Council (JROC), the Defense Planning and Resources Board (DPRB) and the Defense Acquisition Board (DAB).

SIMULATION, TRAINING AND INSTRUMENTATION COMMAND (STRICOM)

On 1 August 1992, STRICOM was established by the Army as a major subordinate command of the Army Materiel Command (AMC). The STRICOM mission is to provide training and test simulation, simulator, target and instrumentation products and services to:

— Develop and sustain warfighting skills

— Create a synthetic environment to evaluate concepts and support requirements definition

— Support materiel development and test and evaluation.

Organized as shown in Figure 6, STRICOM manages more than 200 projects to coordinate and advance distributed interactive simulation (DIS) architectures and standards with the oversight of the DMSO through a Memorandum of Agreement dated 16 September 1992. The STRICOM provides DIS technical management for the Army and is responsible for developing the Battlefield Distribution Simulation-Development (BDS-D), the follow-on to the Simulation Network (SIMNET). The STRICOM develops DIS standards and maintains configuration management of DIS architecture. As manager of the Combined Arms Assessment Network, STRICOM maintains sites at Fort Knox, Ky., and Fort Rucker, Ala. Army guidance on the functional require-

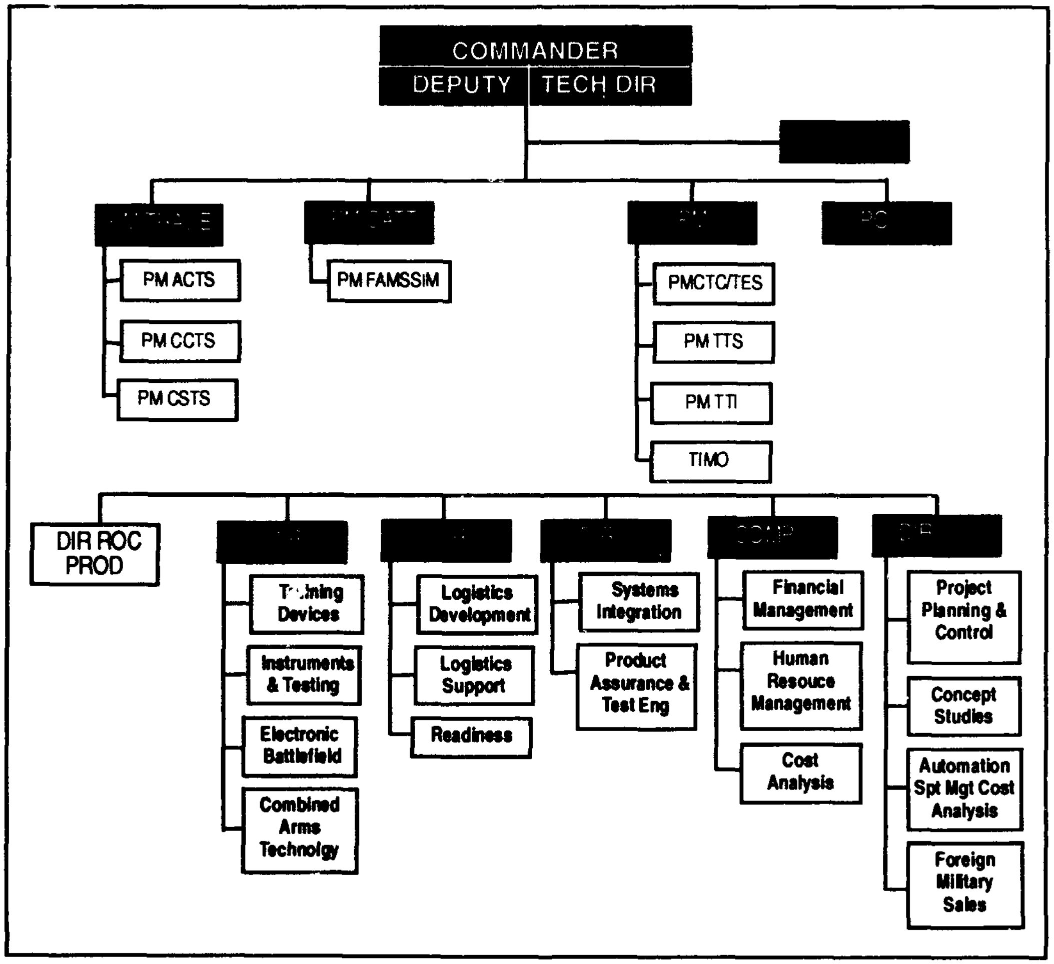


Figure 6. **Simulation, Training and Instrumentation Command (STRICOM)**

Army's Science and Technology Program Distributed Interactive Simulation (DIS) Functional Requirements List (as of 20 November 1992)

The priority order is as follows:

1. Advanced Precision Strike Top Level Demonstration
2. Common Ground Station Advanced Technology Demonstration
3. RFPI Top Level Demonstration
4. LOSAT Technology Demonstration
5. Stingray Technology Demonstration
6. Rotorcraft Pilot's Associate Advanced Technology Demonstration
7. CAC2/Combat ID Advanced Technology Demonstration
8. Advanced Vehicles Technologies Top Level Demonstration
9. Tractor Hip Technology Demonstration
10. TACAWS Technology Demonstration
11. Armor Antiarmor Advanced Technology Demonstration
12. Generation 11 Advanced Technology Demonstration
13. STRATA Demos
14. Electric Gun Virtual Prototype Technology Demonstration
15. Virtual Factory Advanced Concept Evaluation
16. Logistics Distributions-Transportation Network
17. Advanced Cargo Aircraft Advanced Concept Evaluation
18. Future Attack Air Vehicle Advanced Concept Evaluation
19. Biological Agent Detection Technology Demonstration
20. Flame and Incendiary Munitions Technology Demonstration

Figure 7. **Army Guidance on DIS Network Requirements**

quirements for the DIS network is represented by the 20 items shown in Figure 7.[13]

The Project Manager for Training Devices (PM TRADE) is dedicated to supporting the Army Combat Training Centers by providing training devices and simulators to enhance the ability of soldiers, leaders and units to perform their mission.

The Project Manager for Combined Arms Tactical Trainer (PM CATT) manages the development of the Close Combat Tactical Trainer (CCTT), a network of manned simulators pro-

viding combined arms and collective training using force-on-force free-play simulation on a virtual electronic battlefield. The manned simulators will include the M1-series tank, M2/M3 Bradley, FIST-V vehicles and dismounted infantry. Fixed and mobile CCTT systems are planned.

The Project Manager for Instrumentation, Targets and Threat Simulators (PM ITTS) manages the research, development, design, acquisition, fielding, modifications and capability accounting of major instrumentation, targets and threat simulators required for Army technical and operational test and evaluation.

The Project Office for Combined Arms Assessment Network (PO CAAN) is responsible for the operation and maintenance of the CAAN and instrumented ranges.

ENDNOTES

1. Department of Defense, "Annual Report to the President and the Congress," January 1993, p. vii.
2. *Ibid*, p. viii.
3. *Ibid*, p. viii.
4. *Ibid*, p. 37.
5. "Defense Science and Technology Strategy," DDR&E, July 1992, p. ES-1.
6. *Ibid*, p. ES-1.
7. *Ibid*, p. ES-2.
8. *Ibid*, p. ES-2.
9. *Ibid*, p. ES-3.
10. Memorandum approving the DOD Modeling and Simulation Management Plan, signed by Donald J. Atwood, Jr., Deputy Secretary of Defense, 21 June 1991.
11. Memorandum establishing an EXCIMS, signed by Donald J. Yockey, Under Secretary of Defense (Acquisition), 26 September 1991.
12. DOD Modeling and Simulation Management Plan, 21 June 1991.
13. Memorandum, "Functional Requirements for the Army's Distributed Interactive Simulation (DIS) Network," Deputy Assistant Secretary of Defense (Research and Technology), 20 November 1992.

That is the biggest fool thing we have ever done.... The [atomic] bomb will never go off, and I speak as an expert in explosives.

— ADM William Leahy, USN to President Truman, 1945

Chapter 3
SPECTRUM OF SYNTHETIC ENVIRONMENTS

The purpose of this chapter is to identify and describe the world of synthetic environments. This environment is defined as:

> *Interconnected simulations that represent activities with a high level of realism ranging from simulations of theaters of war to factories and manufacturing processes. They are created by a confederation of computers, connected by local and wide area networks and augmented by super-realistic special effects and accurate behavioral models. They allow complete visualization of and total immersion into the environment being simulated. They represent the "real world" precisely.*[1]

In this chapter, the discussion of synthetic environments is divided into four sections. The first on design tools includes the use of computers to design and manufacture systems and subsystems encompassing computer-aided design and manufacturing, stereolithography and virtual prototypes. In the second section, we discuss virtual reality. The third section explains simulation. The chapter ends with an assessment of the enabling technologies which make synthetic environments and virtual prototyping possible.

COMPUTER-AIDED DESIGN AND COMPUTER-AIDED MANUFACTURING (CAD/CAM)

The availability of reasonably priced, highly capable computers and design software has changed radically the design process and its relationship with manufacturing. Using various software packages, design engineers can create a set of detailed drawings for each part used in the design, perform stress analysis on the design through simulation, and ultimately convert the data files into detailed engineering drawings and visualizations. Designs can be produced not only in a fraction of the time required using manual tools, but they match precisely the strength of the structure with the anticipated operating loads and incorporate manufacturing constraints yielding a product that is designed to match, in detail, the requirement with what can be manufactured readily.

There has been tremendous growth in the market for CAD/CAM hardware and software. Total sales have grown from $3 billion in 1985 to $12 billion in 1992; however, the

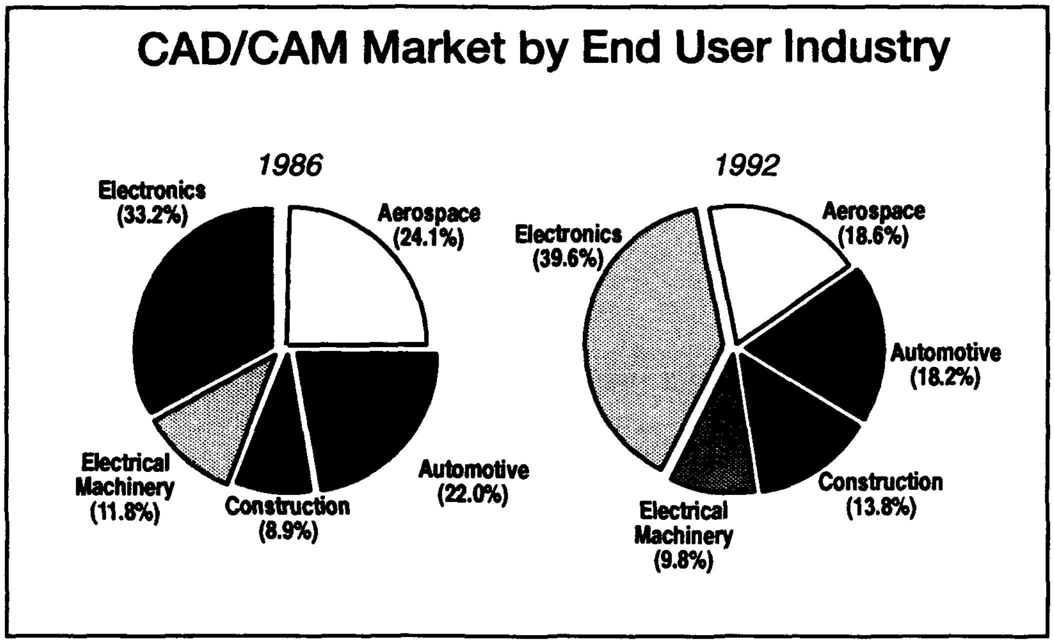


Figure 8. **CAD/CAM Market Changes (Source: Zied)**

rate of growth has slowed during this period from 27 percent per year in 1985 to 17 percent per year in 1992. Figure 8 shows the growth that has taken place in the electronics and construction sectors at the expense of aerospace, automotive and electrical machinery sectors from 1985 to 1992.[2]

Computer-aided design is best defined as a process that uses computers to assist in creating, modifying, analyzing or optimizing a design.[3] The CAD tool is a combination of hardware and software that enhances an engineer's performance. In the hands of a qualified design engineer, it is a tremendous asset, capable of greatly accelerating design and yielding more robust designs incorporating detailed consideration of the manufacturing process and capabilities, all at a lower cost. The principal design-related tasks performed by a CAD system may be grouped into three categories as follows.

Modeling

The CAD tool is used to construct graphic images of an object using basic geometric entities such as points, lines and circles.[4] The designer can manipulate the images by scaling, transforming and rotating. With this computer-based flexibility, the designer can experiment with various design alternatives. There are 2-D "surface" and 3-D "solid" models; the latter contain a full description in mathematical terms of the volume of the object. Presently, solid modeling is considerably more expensive than surface modeling, but it allows the user to analyze mass properties, interferences and fit. Color Plate 1, Advanced Computer-Aided Design (ACAD), courtesy of Lockheed, Fort Worth Company, contains examples of modeling capabilities which include: wire framing, surfaces, solids, analysis, visualization and associativity. Each of these functions is described in Figure 9. These plates were generated by IBM's Computer-Aided Three Dimensional Interactive Appli-

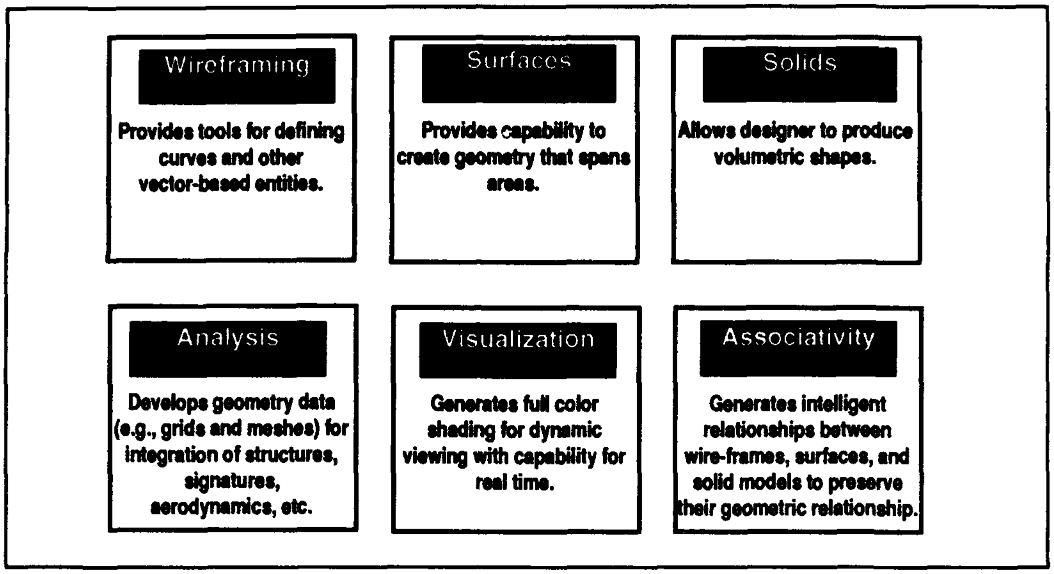


Figure 9. **Modeling (Source: Lockheed, Fort Worth Company)**

cations (CATIA) software package, a series of application programs that forms a highly integrated design, analysis and manufacturing system.[5]

Data visualization is the technique of displaying data using colors and/or shapes to represent numerical values. The values of the data can be magnified to give the appearance of greater variations, allowing the engineer to detect significant aspects. While the data may be visualized in abstract forms, it is usually more useful to drape the data over the CAD model of a component to relate model output to physical locations. For example, heat gradients displayed on a component allow the engineer to understand the process of heat transfer and identify critical spots. Also, by constructing a series of visual displays and playing them in sequence, the data can be animated to reveal more detail about the process being modeled. Thus, heat flows or vibrations can appear to move, allowing the engineer a new perspective in understanding the data. Data visualization is akin to simulation since simulation can be defined as implementing a model over time.

The CATIA provides visualization and is being used by Boeing in the design of the F-22 and the 777 aircraft. They are employing surface modeling on the F-22 and solid modeling on the 777 aircraft. The CATIA family of programs is typical of the design packages available today. It allows the user to create conceptual designs quickly, view the designs, and perform analysis. The common database can be used concurrently by all users. See Figure 10, on the following page. This provides a unique flexibility allowing designers of different parts of an assembly to use different tools, while maintaining a common database.

Another example of the capabilities of today's design software packages is Parametric's Pro/Engineer software package. It is parametric, meaning the user must define general features and relationships of a part or assembly and the system develops solid models. When the user changes a dimension, the part

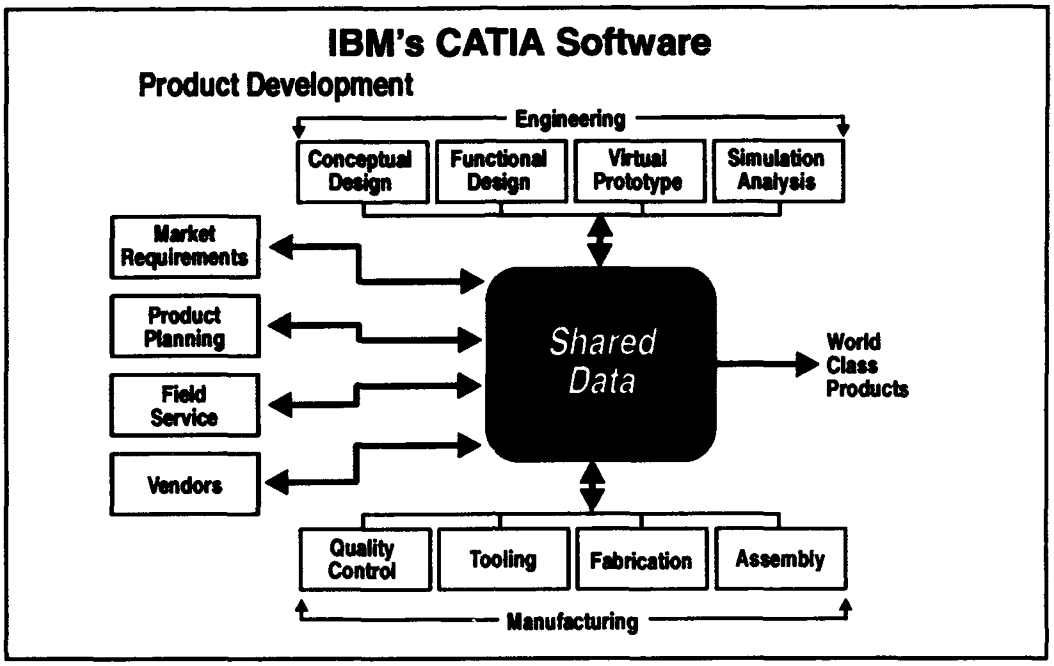


Figure 10. **CATIA's Common Database (Source: IBM)**

changes shape automatically. Pro/Engineer is feature-based also, meaning all mechanical parts can be defined by features such as slots, holes, chamfers, etc. For example, sketch a telephone and the tool automatically interprets the sketch and displays a fully-dimensioned object.[6] Typical of the design software packages available today, the package addresses the entire development process from design to manufacturing.

Meshing

Engineering models are mathematical representations of real world conditions whose purpose is to solve engineering design questions. These models focus on specific problems such as flight dynamics, heat transfer, mechanical stress, vibration and electromagnetic effects. Since they are often constructed for unique circumstances, integration into larger models or simulations is difficult. Engineering models are usually closed form with no human interaction possible; they run "off line" in batch mode. The output is in tabular printouts and interpreted by charts and graphs.

Finite element analysis (FEA) is one class of advanced engineering modeling. Rather than applying a complicated (and often intractable) mathematical model at the macro level to a component, the component is conceptually divided into many small finite elements through "meshing." Each element can then be easily modeled and solved individually. The component performance is the sum of the response of each finite element. Automated tools are available which can input either 2-D or 3-D CAD drawings of components and divide them into finite elements. Once subdivided, models for the effects being investigated may be applied.

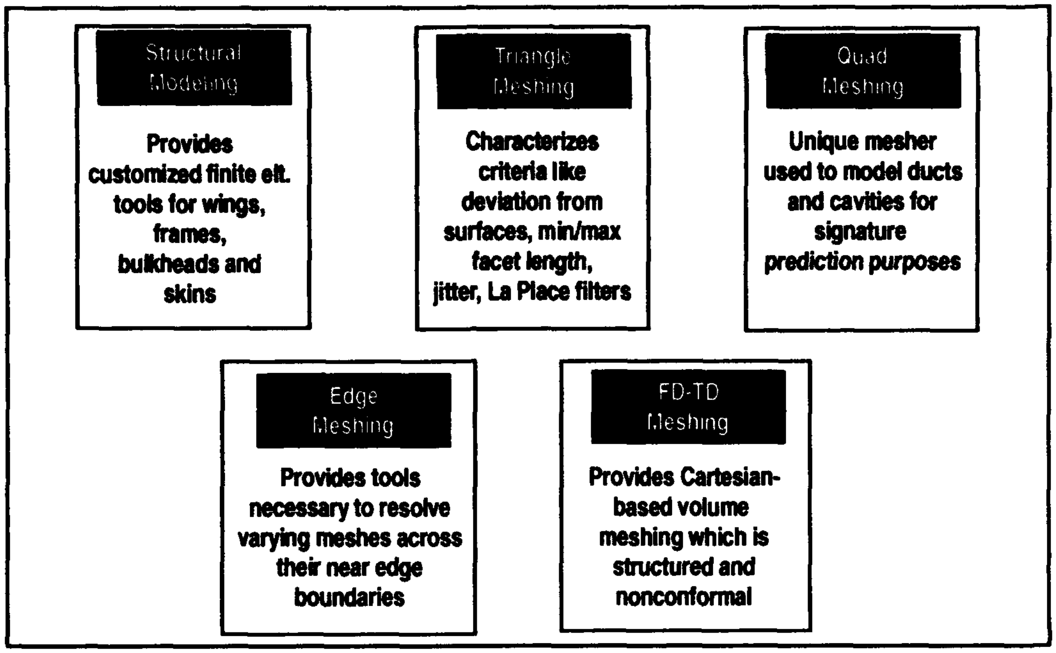


Figure 11. **Meshing (Source: Lockheed, Fort Worth Company)**

Mesh generation forms the backbone of finite element analysis. Meshing refers to the generation of nodal coordinates and elements and includes the automatic numbering of nodes and elements based on a minimal amount of user-supplied data. Automatic mesh generation reduces errors and saves much user time, thereby reducing FEA costs.[7] Color Plate 2, page 124, contains examples of meshing capabilities including structural modeling, triangle meshing, quad meshing, edge meshing and finite difference-time domain (FD-TD) meshing, which are described in Figure 11.

Engineering Analysis

Designers can use software to perform an engineering analysis, such as dynamic simulation and FEA.[8] Color Plate 3, page 125, also courtesy of Lockheed demonstrates the kinds of analyses performed by Advanced Computer-Aided Design (ACAD) tools. These functions are described at Figure 12, on the following page. The FEA enables designers to evaluate complex structures quickly and accurately. Most CAD systems can perform analyses of properties such as surface areas, weights, volumes, centers of gravity and moments of inertia. These tools can be used on parts, sections or entire systems. At the McDonnell Douglas Long Beach facility, design engineers used Automatic Dynamic Analysis of Mechanical Systems (ADAMS) software to analyze the load required on an actuator arm they were evaluating to determine its performance as a closure device on a cargo door of the MD-11 aircraft. The model allowed the user to specify material properties and perform simulation under various flight conditions to determine if the closure device would work properly.

The CAM is the technique of using computers and software to aid in assessing manufactur-

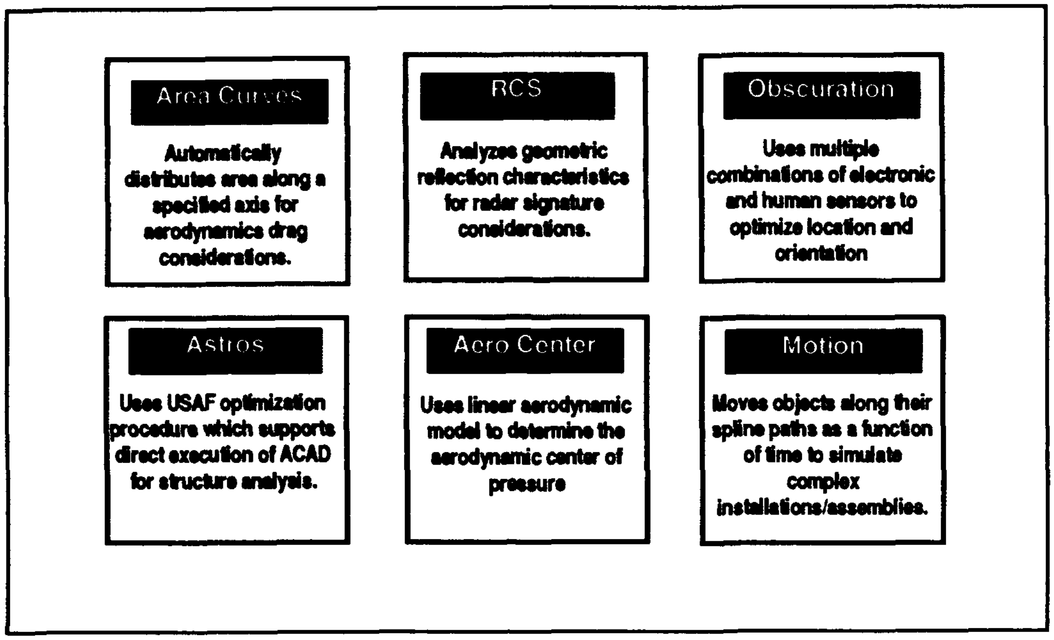


Figure 12. **Engineering Analysis (Source: Lockheed Company)**

ing capabilities and to plan for manufacturing including processes, tooling and material handling.[9] An integrated CAD/CAM system provides for the exchange of information between design and manufacturing functions. The CAM tools evaluate the feasibility of producing the designed product economically, considering quality control, tooling fabrication and assembly. In this manner, the computer allows designers and manufacturing personnel to coordinate the design to ensure the item can be produced. Additionally, since CAM has become the virtual standard for high accuracy machining in the United States, numerical control (NC) data can be drawn directly from CAM data files.[10]

The ability to incorporate manufacturing considerations in the design process and then translate CAM data into NC instructions has been a key element in industry's adaption of CAD programs. Industry has embraced CAD/CAM due to its payback derived from lower manufacturing costs resulting from fewer design changes, parts fitting together the first time and designs being producible. Due to the ease in sharing data, design and manufacturing, engineers can assess the feasibility of manufacturing an item and then modify the design or the manufacturing processes to produce it. Good examples of the relationship between design and manufacturing were seen during our visits to the Boeing Company and the Kohler Corporation where the advantages of CAD/CAM tools were demonstrated at both ends of the manufacturing spectrum, from the sophisticated 777 aircraft to 18-20 horsepower engines. In both cases their design tools have provided a clear competitive advantage in their respective markets. These applications are discussed in Chapter 4.

As illustrated during our visits, CAD/CAM tools are a significant source of competitive advantage to design and manufacturing companies. After Parametric Technology Corporation announced plans to open a sales office in Japan last year, the software maker received an unusual letter from an engineer at a large U.S. manufacturer, "I cannot overcome the sense of foreboding...putting such a powerful tool in the hands of historically strong and successful competitors," he wrote, calling it a weapon the Japanese can use "to make our life hell." The article went on to quote Mr. Stacy Wolf, a product developer at Rubbermaid Inc., "Designs that might have taken a month can often be done in a matter of hours."[11] Mr. Darryl Miller, an engineer at Eastman Kodak Co., says his team has cut the time it takes to design new parts by 50 percent. Other CAD/CAM vendors include Autodesk, Structural Dynamics Research, International Business Machines and Computervision.

The benefits of CAD/CAM tools depend on the qualifications of the users and on management's effectiveness in program implementation. According to Mr. Peter W. Chevalier, OIR Europe, in an article written 10 years ago, the savings which can be achieved are as shown in Table 2.

Based on these averages and considering the total cost of the system including hardware, software and personnel, it is reasonable, according to Mr. Chevalier, to expect a return on investment in one or two years.[12] Future savings can far exceed a company's investment. Boeing plans to achieve these savings on their 777 and F-22 programs. Kohler has achieved these results on their small-engine line. Growth in this area is powered by these savings and the competitive pressure for better products in less time. Today's CAD/CAM tools offer reduced design and manufacturing costs, shorter cycle times, better and customized designs – not without risks, however.

Table 2.
Savings Using CAD/CAM Tools

ACTIVITY	SAVINGS
Setup Time	20 - 60%
Planned Labor	15 - 25%
Tooling	15 - 25%
Rework and Scrap	15 - 75%
W.I.P. Carrying Costs	20 - 50%

Risks

Professor Eugene S. Ferguson's book, *Engineering and the Mind's Eye*, takes a probing look at the process of engineering design; arguing that, despite modern advances, engineering is still as much intuition and nonverbal thinking as equations and computation.[13] The section of his book dealing with "Design Failures and Other Surprises" is contained at Appendix F.

He concludes that engineers need to be reminded continually that nearly all engineering failures result from faulty judgments, not from faulty calculations. Today's designers have no way of knowing the critical assumptions contained in today's commercially-available analytical programs. Consequently, the designer must either accept on faith the program results or check them sufficiently to be satisfied the programmer did not make dangerous assumptions or omit critical factors and the programmer reflects fully the subtleties of the designer's unique problems. This caution applies equally to computer-based simulations.[14]

Challenges

Two major technical challenges are associated with CAD/CAM tools that have a bearing on weapon system design. The first relates to visualization and the second to data ex-

change. In visualization, the problem is displaying 3-D objects and scenes on 2-D scenes. The most common solution to this is "magic carpet" or "fly through" capabilities where the user can travel through an object with his cursor, changing direction and speed to view the object from different angles. Though a cumbersome process, designers almost universally were comfortable with this technique. Other visualization alternatives include high-fidelity simulators, 3-D glasses, and head mounted displays (HMDs), none of which is embraced by designers due to a combination of factors including cost, capability, fidelity and utility.

The second major challenge facing designers is the maze of CAD, CAM and Computer Integrated Manufacturing (CIM) systems in place that designers must navigate through to bring a product to market. While specialized tools and databases abound, the connections among them are *ad hoc*. In design environments, computational tools do *not* usually interact with respect to a shared model: designers do; tools don't. The challenge is to move toward an environment where design tools interact through a shared, explicit model of the design.

This area is being investigated by The Palo Alto Collaborative Testbed (PACT), a laboratory for joint experiments in computer-aided concurrent engineering. It comprises research groups from Stanford, Lockheed, Hewlett-Packard and Enterprise Integration Technologies. The PACT studies have identified two key issues from a designer's perspective:

— How to bridge the multitude of models to support a complex design at various stages of the design process

— How to manage the flood of information associated with a design so everyone stays informed but no one drowns.

Difficulties associated with supporting large-scale distributed engineering systems are especially evident in the design of systems that combine mechanical, electrical and software components. Initially, researchers thought the interoperation of tools across heterogeneous platforms would be a significant problem. This turned out to be a relatively easy task. The harder and more fundamental task facing researchers was agreeing on concepts and terminologies that could be shared by the various disciplines. For example, users must bridge differences in abstractions and views, such as position and time, shape, behavior, sensors and motors, what they mean and how they are represented.[15] Successful design of systems requires an intimate understanding of interactions among different disciplines and subsystems so cross-disciplinary trade-offs can be made. Developing such an understanding is one of the major goals of concurrent engineering.

STEREOLITHOGRAPHY

Stereolithography and material deposition techniques are two principal processes used to produce rapid prototypes. Stereolithography apparatus (SLA) equipment was first marketed in 1988. Using lasers and a special light-sensitive liquid plastic, designs are transformed into plastic prototypes, dimensionally-scaled models or limited-run production samples, often in a matter of hours. Prototypes can be produced from any of the more than fifty 3-D CAD solid and surface data sets and, if necessary, by reverse engineering existing parts. Current systems can produce parts up to 20 x 20 x 24 inches, and multiple parts can be produced and joined together to produce larger pieces with a high degree of accuracy (+/- 2.5 Mil).[16] The 3-D Systems, Inc., has produced and installed approximately 300 machines worldwide — 200 in the United States. At least eight companies offer these systems. Conceptually, the market can be split roughly into two major ap-

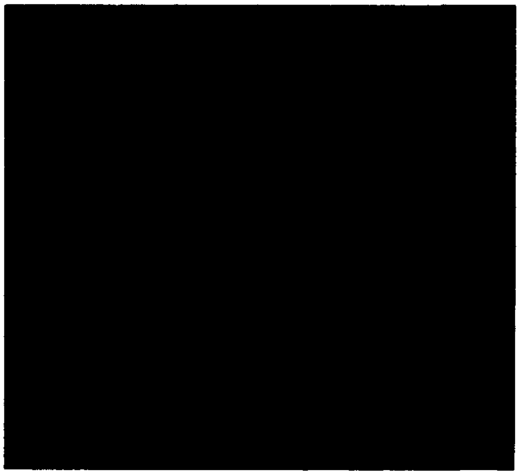


Figure 13. **Green Bank Telescope**

proaches. In most widespread use is the photopolymer-based system, a chemical process in which liquid resin converts to a solid polymer after exposure to ultraviolet radiation or a visible light source. A second front comprises systems using various material deposition techniques to fabricate parts. These tools facilitate rapid prototyping, the process allowing designers to produce prototypes quickly, avoiding the time and cost of tooling and cutting processes.

In addition to on-site installations at major developers, stereolithographic services are being provided by 3-D CAM, a service company located in Canoga Park, Calif. General Motors recently imposed a prerequisite that all parts requiring tooling must employ stereolithography. To comply with this requirement, they have seven stereolithography machines. A discussion of the costs of this equipment appears later in this report.

The principal advantages of stereolithography include:

— *Rapid Prototyping.* Prototypes that can be built rapidly, and are used to communicate quickly and realistically the appearance and major functional requirements of any product. It is a logical progression from auto CAD machines with their 2-D models to 3-D prototypes. The 1/200 (1.5 ft.) scale model of a Green Bank Telescope, built by National Radio Astronomy Organization, will be the largest steerable radio telescope in the world. See Figure 13.

— A stereolithographic model was produced from a CAD files in 10 weeks by 3D-CAM Inc. Engineers from Jet Propulsion Laboratory created a file of data points with dimensions of components and 2-D drawings with Pro/Engineer software from Parametric Technology, Waltham, Mass. Then, the data was converted into ".STL" files — stereolithography compatible file format at 3D-CAM. The antenna structure is a truss construction of more than 6,500 pipes. The model was tested in a wind tunnel with winds up to 70 mph.[17]

— *Concurrent Engineering.* Prototypes are a direct link to the production process — investment casting, die casting, rotational casting, sand casting, injection molding, blow molding and thermofolding. With prototypes, design engineers can better assess and modify designs to meet user requirements and manufacturing capabilities. Stereolithographic parts also make it easier to test accurately for fit and possible interference. The process was used by 3D-CAM to produce a magnesium motorcycle wheel in 20 days.[18]

— *Procurement and Fabrication.* Models enhance communication with vendors. A company can send prototypes to vendors of complex parts or subassemblies for quotes.

— *Marketing.* Models can be shown to customers to demonstrate the physical properties

of the product and making design modifications before tooling production.

Other items made using stereolithography demonstrated the full range of applications. A master stereolithography part was used to make silicone rubber molds that were later used to cast accurate prototypes in polyurethane or epoxy material with close resemblance to the thermoform plastics of the final product. It provides for rapid prototyping since parts take hours instead of weeks to build, reducing overall costs.

Stereolithography systems are expensive. The 3-D Systems SLA 250 is capable of producing parts as large as a 10 inch cube and the SLA-500 can produce parts as large as a 20 inch cube. The systems range in price from $120,000 to $420,000 including the cost of the laser system, a work station, and a curing oven. As promising as the technology sounds, however, sales by 3-D Systems after growing rapidly in the late 1980s fell in 1991 and 1992.[19]

VIRTUAL PROTOTYPING

The DOD defines a virtual prototype as:

> *A computer-based simulation of a system or subsystem with a degree of functional realism comparable to a physical prototype;*[20]

and virtual prototyping as:

> *The process of using a virtual prototype, in lieu of a physical prototype, for test and evaluation of specific characteristics of a candidate design.*[21]

A virtual prototyping environment is a multidisciplinary collection of models, simulations and simulators focused to guide product design from idea to prototype, emphasizing subsystem optimization and integration rather than hardware. In the context of military procurement, a virtual prototyping environment would address: engineering design concerns of the developer, process concerns of the manufacturer, logistical concerns of the maintainer, and training and doctrinal concerns of the warfighter.

A new generation of simulations is envisioned that will enable creation of realistic synthetic battlefields bringing warfighters, developers, scientists, engineers testers and manufacturers together. Virtual prototypes will be tested in simulated combat environments. Concepts will be explored before bending metal; system attributes and capabilities can be changed rapidly on the synthetic battlefield. Once a concept is approved, design and manufacturing trade-offs will be conducted on the virtual prototype to enhance producibility and eliminate the need for a physical prototype.

The concept of a virtual prototype and the application of virtual prototyping is a critical element of the Science and Technology (S&T) Program and its goal of minimizing and accommodating a smaller force structure, improving joint operations, and retaining the technological edge against all potential threats. The S&T Thrust Six, Synthetic Environments and Thrust Seven, Technology for Affordability incorporate the virtual prototyping concept in the overall S&T Program.

Synthetic environments are defined by the Defense Modeling and Simulation Office (DMSO) as internetted simulations that represent activities at a high level of realism from simulations of theatres of war to factories and manufacturing processes. These environments are fundamentally different from the traditional simulations and models known today. They are created by confederations of computers, connected by local and wide area networks and augmented by super realistic

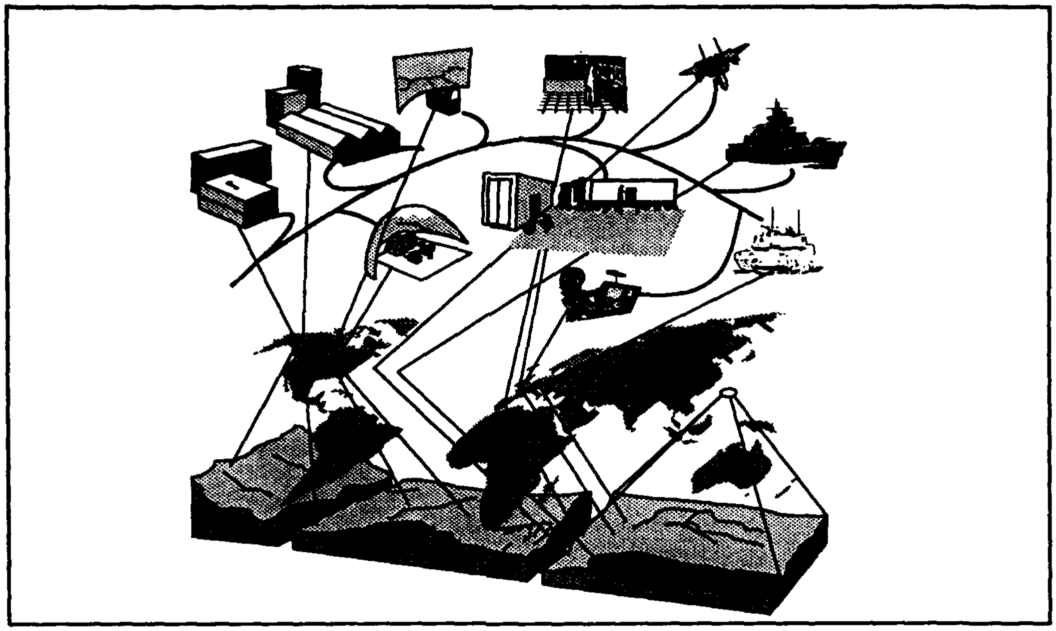


Figure 14. Synthetic Environments (Source: DDR&E)

special effects and accurate behavioral models which allow visualization of, and total immersion into, the environment being simulated.[22] It is envisioned that virtual prototypes will be inserted in synthetic battlefields, consisting of a simulation of the components of an actual battlefield (air, land and/or sea), to assess system capabilities during the acquisition process. Once systems are fielded, simulations will be used for training, doctrine and organizational purposes. See Figure 14.

At a synthetic environments conference in December 1992, the Acquisition Research Project Agency (ARPA) representatives stated, "Simulation represents an opportunity for the acquisition community to take full advantage of advanced distributed simulation throughout the development cycle within the warfighter's environment." Colonel Jack A. Thorpe, USAF (Ret.), Special Assistant for Simulation at ARPA, envisions that by the end of the decade using simulation we will have the capability to visualize the battlefield as the warfighter sees it, and our combat forces will always be at "war" in a Louisiana Maneuvers 12 months a year; thus, enabling mastery of joint warfighting doctrine.[23]

Principal challenges of synthetic environments and virtual prototypes include creating environments that are meaningful and realistic to human participants; having computers accurately represent human behavior; creating environments that accurately describe real-world places; and connecting globally located sites economically.[24]

A recent MITRE study concluded that the following must be accomplished in order to reap the full benefits of synthetic environments:[25]

— *Technology.* Models need to be more credible reflecting a broad spectrum of behavioral and environmental effects;

— *Strategy.* A well-articulated simulation strategy is required at the outset of a program;

— *Evolution.* The government and contractor need to develop a game plan addressing the environment and system operation in the environment;

— *Verification, Validation and Accreditation (VV&A).* A practical approach needs to be promulgated.

The objective of Thrust Seven, Technology for Affordability, is to reduce costs and the time it takes to make an acquisition. According to ARPA, the targeted capabilities are:[26]

— Simulation-based evaluation of requirements and capabilities

— Integrated product and process development

— Responsive, flexible manufacturing processes

— Integrated enterprise systems and supplier relationships

— Integrated, real-time management control systems.

Virtual prototypes are an important ingredient to the success of these initiatives. Produced today with existing CAD/CAM tools, they offer tremendous potential for reducing costs, yielding more robust designs, and shortening manufacturing cycle times. Companies are reaping significant benefits from using virtual prototypes and achieving the capabilities desired of Thrust Seven. Companies are finding physical prototypes are no longer necessary and simulation-based tools enable them to achieve competitive advantage. It is important to note these advantages are being accomplished using existing computer tools at current costs. As the capabilities of these tools grow and costs lessen, companies will have no choice but to use virtual prototypes to compete.

The concept of the "virtual factory" is also part of Thrust Seven. A simulated factory could be used to: identify designs requiring modification to enhance producibility; determine which processes should be automated; assess the feasibility of dual-use technologies, and calculate surge capability. Research is taking place on the "virtual factory" where the concepts of rapid prototyping, flexible manufacturing, commercial vs. military requirements, and industrial base issues are being explored. The number of applications, however, are extremely limited.

VIRTUAL REALITY

Virtual reality (VR) is a subject of enormous curiosity to government, industry and academia. The term is often used interchangeably with a number of related names such as virtual environment, telepresence, virtual prototyping, electronic battlefield, virtual factories, synthetic environments, scientific visualization, cyberspace, etc.[27] Confusion over the definition stems from the vast array of potential customers eager to characterize their product as "virtual." Laying the hype aside, the technology, according to experts in the field, offers great potential in science and engineering research, education, entertainment, design, financial analysis and defense simulation. The operative word is "potential" because most applications are concentrated primarily in the entertainment field where Hollywood views visualization as a locomotive for the future of growth in digital technology and VR. Recently, IBM Corporation entered into a joint venture with Digital Domain where it hopes to reignite its growth by sparking demand for powerful computers and software needed to handle huge amounts

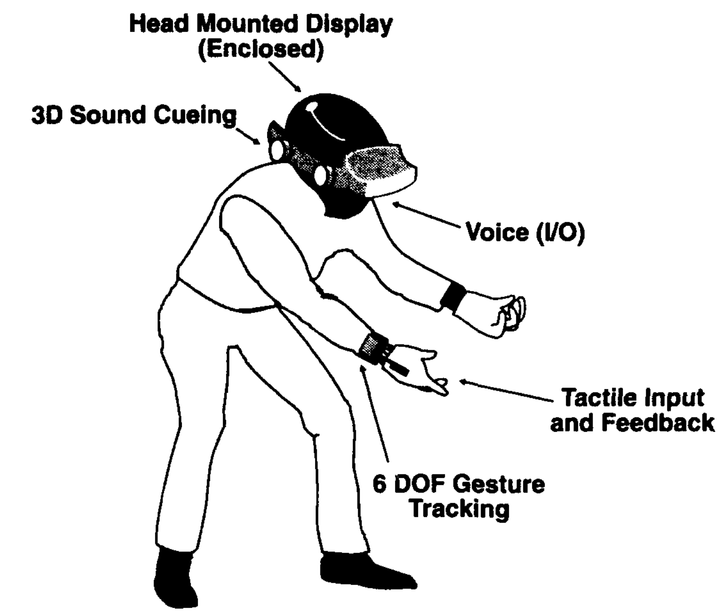


Figure 15. **Equipment Used in a Virtual Environment (Source: NASA/Ames)**

of digitized visual information, such as special-effects movies and video conferences.[28]

The best description of VR comes from Dr. Thomas A. Furness III, Director of the Human Interface Technology Laboratory, a division of the Washington Technology Center, University of Washington:[29]

> *Virtual reality is an environment that you create using a combination of visual, auditory, images - things that you see, things that you hear, things that you feel - that appear to be coming from a location in space, but aren't really there..*

Harold Rheingold expands upon this in his book, *Virtual Reality*, by characterizing VR as:[30]

> *The ultimate computer interface. The virtual world is a computer that you operate with natural gestures, not by composing computer programs, but by walking around, looking around, and using your hands to manipulate objects.*

The essence of virtual reality, and its many related terms, is the capability of providing a means to visualize complicated systems and databases and to produce simulations in a real time, seamless network of models. A virtual system must have the following minimum attributes:

— *Authenticity.* It must be perceived as real and authentic

— *Immersion.* It must immerse humans so interactions with this environment are intuitive

— *Validation.* It must be validated and accredited for the application

— *Interaction.* It must be interactive and rapidly reconfigurable.

The equipment utilized in a virtual environment is depicted at Figure 15, courtesy of the NASA Ames Research Center. The system consists of: a wide-angle stereoscopic display unit, glove-like devices for multiple degree-of-freedom tactile input, connected speech recognition technology, 3-D sound cueing and speech synthesis technology, and gesture tracking devices.[31] To create the visual illusion, two slightly different computer-generated views are projected on tiny liquid crystal screens inside the goggles. This produces the 3-D effect of normal vision, created by the fact that neither eye perceives the same thing from exactly the same perspective.[32]

The VR equipment is expensive. The VPL Research of Redwood City, Calif., principal supplier of VR headsets and data gloves, sells the headsets for $10,000 to $49,000 each and the gloves for $8,800. Most existing VR systems require the power of a supercomputer. The VPL system uses two powerful Silicon Graphics computers, one for each eye. Total system cost can easily run to $250,000 and more. To reach the mass market, costs must be cut drastically.

Mattel markets a $50 version of the data glove. Controlled by a $99 Nintendo game cartridge, the glove allows its user to play virtual handball on a virtual court against a virtual opponent. Since introducing the glove in 1989, Mattel has sold a million of them. The VPL is working on a $200 data glove for PC users. Add a pair of stereo glasses ($1,300), put a virtual reality chip board (another $1,000 to $2,000) in your PC, and off you go into an inexpensive version of artificial reality with a cartoon-like quality.[33]

One of the biggest challenges facing researchers, according to Frederick P. Brooks, Jr., a professor in the computer science department of the University of North Carolina at Chapel Hill, is reconciling realism with interactivity. Real-time motion, complex world models, and high-quality images create a workload that overwhelms todays hardware.[34] Visual images in today's head-mounted displays are cartoon-like, and the headsets are bulky due to the awkward umbilical cable, which restricts movement, connected to the computer. Another problem is the tendency of some operators to become ill while using the head-mounted displays.

The term virtual reality is new but much of what we know about personal computing grew directly from Engelbart's Augmentation Research Center (ARC) at the Stanford Research Institute in the 1960s where several VR taproots originated. Today, simulation technology has advanced to permit "sensory overload" through all human receptors simultaneously — visual, auditory, haptic and motion interfaces. The term "haptic" refers to any variety of manual interactions with the environment.

Systems are extremely complex and must rapidly interact in proper context with many disparate entities. A VR machine is intended to immerse humans into real-time interactions so they may learn, train, test, have fun or understand and optimize processes and systems. The virtual environment could also be selectively constrained by policies, resources, tactics, or strategies to correctly represent the customer issues.

Scores of conferences, working groups, and other forums have discussed virtual reality and related topics. Most of these conferences have focused on the technical aspects of virtual reality but, increasingly, issues of policy, management and resources are being discussed. It is beyond the scope of this report to summarize the outcomes of all those meet-

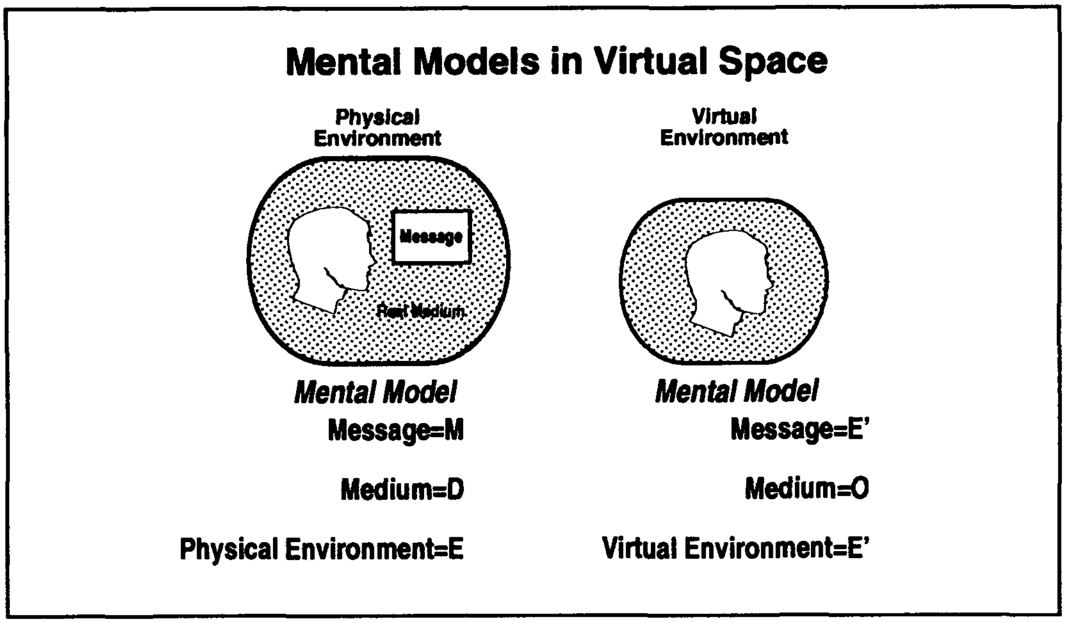


Figure 16. **Mental Models in Virtual Space**
(Source: Dr. Thomas A. Furness III, University of Washington)

ings; however, it would be instructive to focus on two of these conferences — IMAGE VI, at Scottsdale, Ariz., 17-18 July 1992, and Virtual Interface Technology (Virtual Reality), at UCLA, 15-17 March 1993 — to emphasize current issues and applications.

Most commonly used terminology in the IMAGE VI conference was "virtual environment." Nine of the virtual environment papers covered topics such as virtual technology training, implications for networked tactical training, battle staff planning and mission rehearsal, advanced networking technologies, dynamic terrain databases, decision support environment for tactical C2, mapping, charting and geodesy synergism, standard simulator databases and interoperability of visual simulation systems.[35]

The Virtual Interface Technology (Virtual Reality) conference addressed virtual interface concepts, human factors considerations, hardware capabilities and software considerations. They defined "virtual world/virtual environment/virtual reality" as:[36]

> *The representation of a computer model or database in the form of a system of virtual images which creates an interactive environment which can be experienced and/or manipulated.*

Dr. Tom Furness, Director of the Human Interface Technology Laboratory of the University of Washington, and former Chief of the Visual Display Systems Branch, Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, Ohio, led the course. While with the Air Force, his staff pioneered advanced interface concepts for fighter aircraft including the Super-Cockpit.

He explained the relationship between the physical or real world with virtual reality by

comparing mental models in each environment: the message (what one sees), the medium (the display device) and the physical environment. See Figure 16. In the virtual environment, the message and the environment are synonymous, the medium nonexistent. The user becomes the part of the message where the he or she can interact with the environment. A spectator becomes a participant.

The primary advantage of VR is its potential to empower humans by developing better ways to interact with computers. According to Dr. Furness, people see images, not objects. He goes on to explain that there are three kinds of visual thinking: 1) the kind we see from objects; 2) the kind we imagine, such as visual images while reading a book; and 3) the kind we create ourselves when we write or draw. The region of maximum creativity is where all three kinds of visual thinking overlap — the virtual world. See Figure 17. The key to empowering humans with virtual reality is to make the computer more human-like rather than requiring the human to be more machine-like.

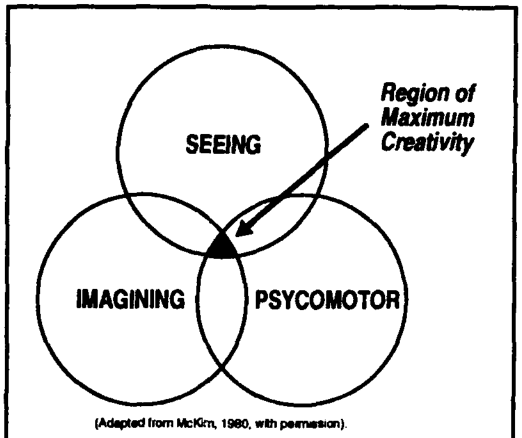


Figure 17. Visual Thinking

The capabilities of the Super Cockpit best represent the capabilities of machines in the virtual world so it is worthy of a brief discussion. Dr. Furness described the virtual cockpit as a control and display medium which organizes and fuses information from aircraft subsystems and portrays this information in the form of a visual, auditory and tactile circumambience for rapid assimilation by the pilot. The simulator enables pilots to operate complex aircraft with natural hand and eye movements and voice control.

A representation of a super cockpit display scene is in Figure 18. A pilot might view this scene when flying at low altitude. It is projected to the pilot in three dimensions and overlays the real world with a one-to-one spatial registration. Critical information is no longer compressed into small two-dimensional representations, but now surrounds the pilot and is seen in three dimensions relevant to the location of the information source. For example, the artificial horizon normally presented in the attitude direction indicator now appears as a panoramic horizon surrounding the pilot and overlayed on the real world. The heading compass now appears impressed over the horizon instead of in a horizontal situation indication in the cockpit. Targets, navigation waypoints, threats, etc., now appear where they really are in space, rather than in a small, two-dimensional presentation in the cockpit. An electronically inserted "rear view mirror" also conveys visually to the pilot what may be behind him.

These displays are augmented with audible and tactile displays. The auditory display gives the pilot a three-dimensional sound which provides localization cues to the locations of different targets, aircraft, threats, etc. Warning signals are perceived as coming from a particular point in the cockpit. A synthesized speaker can even whisper in his ear information which cannot be ignored.

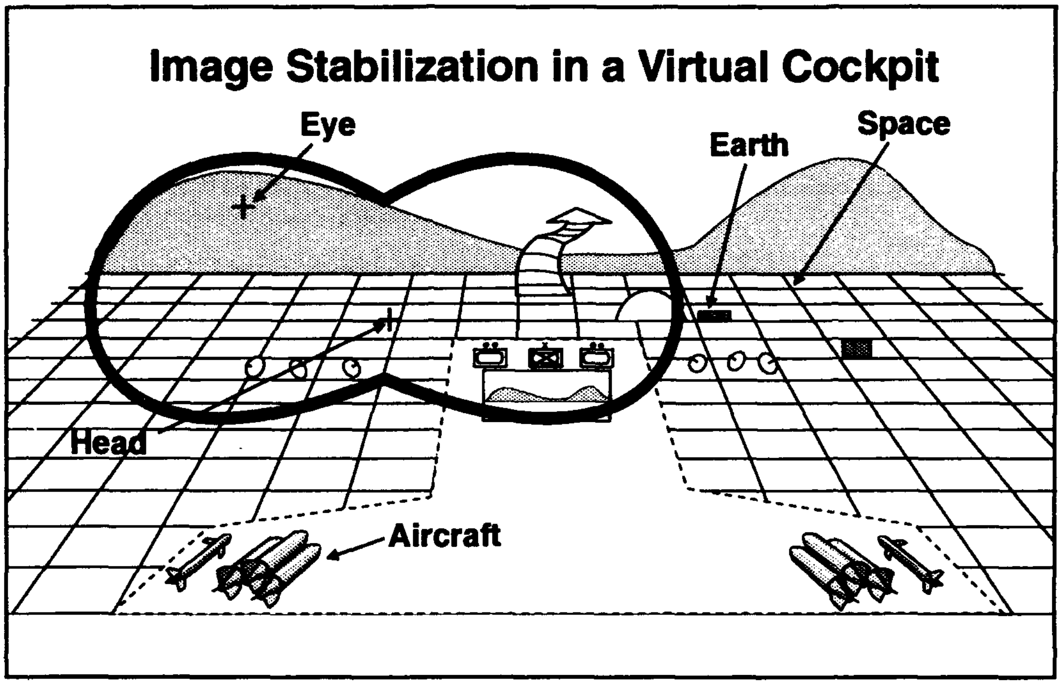


Figure 18. **Super Cockpit Display Scene (Source: HITL)**

The VR has tremendous potential in the entertainment industry where significant investment is being made. Virtual World Entertainment LP's VR game site in Chicago, the "Battle-Tech Center," sold approximately 300,000 tickets at $7.00 each between July and September of 1992 to players who sit in an enclosed cockpit to engage in Star Wars-like battles. The company has two sites in Japan and plans to open 17 or more over the next three years.[37]

Resolving technical and resource issues depends on the customer. However, issues of policy and management of multicustomer synthetic environments may have to be determined at a higher level or by cooperation. Consider the range and variety of customers: education, entertainment, science and engineering, defense and industry. Then consider only the Department of Defense (DOD) and the five separate customer subgroups: (1) Research, Development and Engineering, (2) Education, Training and Military Operations, (3) Test and Evaluation, (4) Analysis and Operations Research, and (5) Production and Logistics. Each subgroup has a different role in the acquisition process, different chains of command, different needs for fidelity, representation of weapon suites, data collection, and characterization of human interfaces. Each synthetic environment evaluation or demonstration within DOD must satisfy the appropriate agencies and decision makers in accordance with existing regulations. Hence, implementation of VR is an extremely complex DOD undertaking.

The VR has the potential of allowing people to interact with complicated physical processes through three-dimensional color visualization and can enhance understanding and knowledge. Its proponents argue it will unleash the creative genius of individuals and

transform business and society. However, applications of VR are rare and one of the leading producers of head-mounted displays recently went bankrupt. Surely offering great promise, it is unclear how this technology will impact defense, business and society.

SIMULATION

Comparing computer modeling and simulation, modeling is the development of equations, constraints and logic rules, while simulation is the exercising of the model over time. Simulations contain models. In order to systematically discuss simulation in general, the topic is divided into classes. There are many possible ways to define the classes: technique of implementation, purpose or objective, level of detail, linkage between models, size of time units, structure of simulation components, deterministic vs. time varying, continuous vs. discrete, physical models vs. human behavior and degree of human interaction, to name a few. The DMSO defines three classes based on the differing evolving technologies used to implement each class. The definitions are:[38]

> COMPUTER MODELS. *Systems and forces and their interaction are primarily represented in computer code. The models can differ greatly in the level of detail of the representation, and there may be some human interaction with the model while it is running.*

> MANNED WEAPON SYSTEM SIMULA TIONS. *Individual weapon systems are modeled (e.g., by a simulator) and typically controlled by a human operator. Principal emphasis is on the situation where the individual simulations interact together through a distributed network. The archetype of this class is SIMNET.*

> INSTRUMENTED TESTS AND EXERCISES. *Actual troops, weapon systems and support systems interact in as real an environment as possible, with instrumentation being used to collect and distribute status data on the force elements. Activities at the National Training Center are a representative example.*

A similar classification scheme appearing in informal papers within DOD defines the following three classes of simulations:

> CONSTRUCTIVE. *Wargames, models and analytic tools developed by the individual Services.*

> VIRTUAL. *Systems simulated both physically and by computer. Real people fight on synthetic battlefields, interacting with each other and with artifacts in the simulation. Examples include individual aircraft simulators and virtual prototypes.*

> LIVE. *Operations with live forces and real equipment in the air, on the ground, on and below the sea. Also included are hardware prototypes on instrumented ranges.*

ISSUES IN SIMULATION

A number of issues concerning the implementation of simulations need to be discussed to understand better how well simulations can serve their intended purpose. These issues are particularly important when using interactive simulations and defining a synthetic battlefield for conducting virtual battles.

First, consider the level of detail in a simulation. Level of detail can be expressed as "fidelity" — the physical correspondence of the hardware to actual equipment; "realism" — the subjective perceptions of the people using the simulation; and "validity" — the suitability of the simulation for a specific application.[39]

The term "fidelity" is often used to refer to all types of the level of detail in a simulation. There is a trade-off between the amount of fidelity and the cost of implementing the simu-

lation. Greater fidelity means greater cost to design, build and maintain the simulation and increased computer power to run the software. Rather than assume one should buy all the fidelity one can afford, the intended purpose of the simulation must be considered. Simulations for operator training may have too much realism which can interfere with learning basic skills and procedures. Models in a simulation may range from single weapon systems to phenomena addressing theater and campaign warfare, and modeling individual infantry soldiers in a theater level simulation is unlikely to improve upon the intended purpose of the simulation.

The cost of computer power to generate a desired level of fidelity is an important trade-off given the limitations of today's computer technology. This is especially true when generating visual images on a synthetic battlefield. Unfortunately, the computing power reasonably available today falls short of that needed to produce high-quality images. However, acceptable and highly useful visual simulations can be built using today's technology.

Second, there is a need to provide semiautomated forces which mimic human behavior. Virtual (interactive) simulations are more effective when fighting with and against intelligent forces. Simulating an Army division in combat can't be accomplished reasonably using a division complement of simulator operators. Rather, semiautomated forces are needed to provide friendly and enemy forces who respond with realism to the terrain, available weapon systems, orders from higher echelons, self-preservation actions, and actions of other forces. Individual infantry men need to be automated. The actions of semiautomated forces must aggregate to produce acceptable behavior of higher echelon formations. Models of realistic human performance and decision making need to be validated. Implementing this degree of realism will require a significant investment in software development.

Third, terrain databases for synthetic battlefields need significant improvement. The fidelity of terrain databases need to be increased to provide more realism by including soil conditions, vegetation, weather effects, more precise elevation data, electromagnetic effects, water obstacle depth and flow rates, obscurants and wind effects and improved detail for man-made objects. Also, the terrain database needs to be automated so changes to the terrain, such as battle damage and excavation, are made during a simulated battle. A synthetic battlefield must present the same conditions to all participants. It is not acceptable to have one weapon system believe it is concealed by a terrain feature in its database while a second weapon system is able to "see through" the nonexistent feature. Nor is it acceptable to allow vehicles to drive across the surface of lakes. Realistic terrain will help provide greater confidence in the conclusions resulting from simulated battles.

Last, there are many unresolved issues concerning VV&A of synthetic battlefields and simulated weapon systems. Within DOD, who has the responsibility for accrediting synthetic battlefields and how will it be accomplished? Standards need to be established and software tools built to facilitate VV&A. If synthetic battlefields are to be used to make major acquisition decisions, VV&A becomes crucial to success.

TECHNOLOGY ASSESSMENT

Of all the enabling technologies which make virtual prototyping possible, shown in Figure 19, many are commercially driven; consequently, DOD can benefit from advances made in the commercial market. Other technologies are of interest primarily to DOD and

ENABLING TECHNOLOGIES	
Commercially Driven	**DOD Driven**
Database management systems	Manufacturing process simulations
Man-machine interfaces	Engineering design models
Software engineering tools	Manned simulators
Local and wide area networks	Stochastic wargaming simulations
High performance computers	Semiautomated forces
Computer image generators	Instrumented ranges
Microcomputer systems	Instrumentation
Microprocessors	Simulation construction tools
Memory	Multilevel security
Mass storage	DOD protocol
Display devices	DOD databases

Figure 19. **Enabling Technologies Making Virtual Protototyping Possible**

will require funding and careful management to produce useful results. The DMSO has identified eight key technology "areas" which provide the foundation for modeling and simulation: database technologies, environmental representation, networking, software engineering, behavioral representation, instrumentation, graphics, and computer hardware.[40] Described below is the status of several of these key areas.

Computer Hardware

During the last decade, computer hardware has improved continuously in processor speed and memory capacity; at the same time, costs have declined. Supercomputers and mainframes capable of high computational speeds and workstations and minicomputers capable of running large simulations are now available. The pace of generation turnover, with each generation representing at least a doubling of capability and possibly a change in basic technology, is one to two years, depending on the component. Microprocessors and microcomputer systems turn over each two to three years, memory and mass storage each three years, local area networks and display technology each four years, and computer image generators each five years. This growth is fueled by the commercial sector and not DOD.

The growth trend is expected to continue throughout the remainder of this decade.[41] Estimates of growth from 1993-98 are that processor performance will grow from the current 50 million floating point operations per second (Mflops) to 1500 Mflops. Memory chip density will grow from 4 million bits (Mbit) per unit area to 256 Mbits. Local area

network performance will grow from the current 10 million bits per second (Mbps) Ethernet and 100 Mbps Fiber Distributed Data Interface (FDDI) to more than 500 giga bits per second (Gbps). One Gbps equals 1,000 Mbps. Wide area networks will increase throughput from T1 rates of 1.5 Mbps to 2.4 Gbps. Computer image generators currently process 10,000 polygons per second and are expected to be a thousand times faster by 1998. The two primary driving forces behind the growth trend are integrated circuit density and parallel computing architectures. At current growth rates the physical limits of integrated circuit construction will be met; however, benefits of parallel architectures are just beginning to be implemented in commercial products.

The University of North Carolina at Chapel Hill has developed a parallel architecture multicomputer called the Pixel-Planes 5 which provides high performance 3-D graphics generation at the rate of 100,000 polygons per second and is capable of generating 2 million polygons per second with a fully configured system. A polygon is defined as a two-dimensional figure whose characteristics are described with approximately 100 bits of information. Using a ring network of specialized graphics processors and separate renderers, each with its own memory, the multicomputer rapidly draws finely detailed images with advanced lighting models and textures. Commercial image generators operate at a rate of 10,000 polygons per second, making the Pixel-Planes 5 multiprocessor an exceptional performer by comparison.

Computer Software

Spectacular improvement in computing hardware alone is not sufficient to ensure major improvement in simulation capability. Software development tools which allow rapid construction of simulations and virtual prototypes are almost nonexistent.

The Human Interface Technology Laboratory, University of Washington, is building a Virtual Environment Operating System (VEOS) to provide a seamless environment which will couple humans into a virtual environment, manage simulation processes, and integrate the output signals to display devices. An operating system such as VEOS can provide a standard interface for software developers, allowing easy integration of products from diverse sources and reusable software. The VEOS will be public domain software.[42]

A commercial virtual reality operating environment titled "dVS" is available from Division, Inc. This system provides high performance operation across multiple hardware platforms and software tools to allow structured design of virtual reality applications. More than 20 dVS systems are in operation, providing 3-D immersive virtual reality applications such as architectural building walk-through and product design visualization.

Head-Mounted Displays

A head-mounted display gives the user the sensation of being immersed in a 3-D computer-generated environment. Head-mounted displays provide stereoscopic views by generating a separate image for each eye. By tracking head movements and position, the computer generated scene can be adjusted to any point of view. The user can move through the environment and turn and look in any direction. Tracking can be accomplished by several means; i.e., movement of a sensor through a magnetic field, sensing light emitting diodes (LED) with a video camera, or direct-coupled mechanical linkages. Only the LED method offers a room-sized movement space today. The magnetic and mechanical trackers are limited to a distance of a few feet. Accurate and rapid tracking of head position is critical to maintaining the illusion of im-

VIRTUAL INTERFACE DESIGN CONSTRAINTS

Parameter	Ideal	Practical
Visual Display		
Fields of View	120 H x 70 V deg	100 H x 60 V deg
Angular Activity	1 min of arc	5 min of arc
Resolution	7200 H x 4200 V pixels	1200 H x 720 V pixels
Refresh Rate	60 Hz	60 Hz
Bandwidth	160,000 Mhz	52 Mhz
Head Positioning		
Rotation Velocity	100 deg/sec	50 deg/sec
Rotation Update Rate	6000 Hz	600 Hz
Translation Update Rate	30 Hz	20 Hz
Throughput Delay	1 msec	50 msec

Figure 20. **Ideal Interface Parameters Compared to Current Practical Limits (Source: Dr. Thomas A. Furness III, University of Washington)**

mersion in a virtual environment and for avoiding motion-induced illness.

A wide variety of head-mounted displays have been developed over the years since Ivan E. Sutherland created the first device in 1965.[43] The primary technical issues to be overcome are weight, width of the field of view, accuracy of the head positioning system, resolution of the display image and the rate of refreshing the display image. A brief description of these issues follows and the quantitative design parameters are shown in Figure 20.[44]

— *Weight.* Excessive weight causes users fatigue. If the center of gravity is not positioned properly, fatigue is increased and motion-induced illness can result. The weight of the display causes an increase in rotational inertia which confuses the user's vestibular system.

— *Field of View.* The area visible without moving the head is the field of view. At least 80 degrees of horizontal field of view is required to give an impression of immersion and avoid a tunnel vision effect.

— *Head Position Accuracy.* The head positioning system needs to detect small increments of motion and update the display without delay. Systems linked to head positioning, such as weapon sighting, need to be coupled accurately.

— *Display Resolution.* The image resolution should be 7,200 pixels horizontal by 4,200 pixels vertical, where a pixel is the smallest element that can be displayed. Most head-mounted displays today fall far short of this goal.

— *Refresh Rate.* The display image must be updated as head position changes. Computer hardware and software performance as well as head positioning accuracy affects

the refresh rate. Displays which lag head movements can cause illness.

Examples of display technologies are:

— Dual LED displays present a separate image to each eye, augmented by optical lenses to increase the field of view. Low cost LED display technology has a low resolution of about 700 by 300 pixels today, but higher pixel density displays are emerging.

— Dual cathode-ray tube (CRT) displays offer higher resolution, but are monochrome. The image resolution is better than LED technology. Full color miniature CRTs suitable for head mounting are not readily available, though commercial products are anticipated within the next year.

— Dual light guns with fiber optic links to the head mount provide color displays with acceptable resolution. Light guns are high-intensity image projectors that cost substantially more than other display technologies. The resolution of the display is limited by the size and number of optical fibers that conduct the image to the head mounted optics.

— Single CRT monochrome displays with shutter lenses alternately present a slightly different view to the left and right eye to give a 3D image. The single CRT is usually supported by a counter-balanced mechanical boom and is not truly a head-mounted display.

Two new ultra-light weight head-mounted monocular displays are available commercially:

— *Private Eye.* A small 2-1/4-ounce display having 201,600 pixels resolution produces a monochrome red image on a black background. When suspended a few inches in front of the eye, the optics produce an image of a virtual 12-inch display three feet from the viewer. The interface is compatible with the International Business Machines Corporation color graphics adapter (CGA) standard.[45]

— *Virtual Vision Sport.* A visor supports a small reflecting lens which produces a 96,600 pixel color image of a virtual 60-inch display 15 feet in the distance. The visor weighs five ounces. The video interface is the National Television Standards Convention (NTSC), common in the United States. A beltpack with either a standard U.S. television tuner or a 900-Mhz receiver/transmitter is available. Stereo earphones are also mounted on the visor.[46]

SIMULATION NETWORKING (SIMNET) PROJECT

The SIMNET is a joint Army and ARPA project using distributed simulation as both a prototype training device and a new technology testbed. The Army's primary use focused on training collective skills of crews and units using low cost training hardware and software. The ARPA sought to use new technology to implement a distributed simulation architecture based on microprocessors, local area networks, wide area networks, new computer image generators, and a modular structure that would facilitate change.

The SIMNET has established a distributed interactive simulation (DIS) protocol standard based on a broadcast scheme; that is, each simulation on the network broadcasts its information to all other participants. Each simulation participant is autonomous and responsible for maintaining his/her status, for sending messages to others, and for interpreting and responding to messages. Figure 21 shows the type of information exchanged on the network. Simulators only communi-

DIS PROTOCOLS

DIS 1.0 PDU	DIS 2.0 PDU (Proposed)
Entity State	Emission
Fire	Laser
Detonation	Transmitter
Service Request	Signal
Resupply Officer	Instrumentation
Resupply Received	Simulation Management
Resupply Cancel	Create Entity
Repair Complete	Remove Entity
Repair Response	Start/Resume
Collision	Stop/Freeze
	Acknowledge
	Action Request
	Data Query
	Set Data
	Data
	Event
	Message

DIS = Distributed Interactive Simulation
PDU = Protocol Data Unit

Figure 21. SIMNET Information Exchange (Source: STRICOM)

cate changes in the world state. A dead reckoning technique is used to reduce message traffic on the network. Each simulator keeps a simplified model of the state of all other participants within its area of interest. Last reported states are extrapolated until a new update arrives. Each simulator also maintains a dead reckoning model of itself and broadcasts an update whenever its state diverges a set amount from the extrapolation. The minimum update interval is 1/15 of a second and a maximum of five seconds.[47] The SIMNET messages are called Protocol Data Units (PDU) and the PDU structure is independent of the type of network being used.

The STRICOM, with DMSO and the Institute of Simulation and Training at the University of Central Florida, is responsible for managing the combined workshops for developing the technical standards for DIS. Representatives from the Army, Navy, Marines, Air Force, other government agencies, industry and academia are participating in the DIS development.

The SIMNET has evolved from use as a training device to a means for evaluating acquisition alternatives. It can be used to study future concepts, vehicles, weapons, tactics, procedures and doctrine.

PHASE I BDS-D GOALS

Operational Capability	Current Baseline
Environmental Effects:	
Day/Night	Day only
Obscurants	None
Weather	None
Terrain:	
150 x 300 Km area	50 x 70 Km area
Changeable Cultural Features	Fixed
Dynamic Terrain	Fixed
Trafficability	None
Improved Fidelity	Marginal
Signatures:	
Thermal, 4 Levels	Very limited
Electromagnetic Emitters	None
Force Representation:	
Crewed Simulators, 8 Level II	20 Level I
80% Software Reconfigurable	Fixed design
Semiautomated Forces, 80 Level II workstations per operator	15 Level I work workstations per operator
Air Defense, Indirect Fire, Electronic Warfare	None
Systems Architecture:	
DIS Standard 2.0	DIS Standard 1.0
Validated Models	Nonvalidated
Configuration Managed Documentation	Incomplete Documentation
Mixed LANs	Identical LANs
Security:	
Secret	

Figure 22. **BDS-D Capabilities Compared to SIMNET (Source: STRICOM)**

BATTLEFIELD DISTRIBUTED SIMULATION-DEVELOPMENT (BDS-D)

The BDS-D is a follow-on development network based on SIMNET success. The BDS-D will focus on providing a warfighting assessment capability network using a soldier-in-the-loop virtual reality approach. Two major issues addressed by BDS-D are the:

— Verification, validation and accreditation of the DIS models

— DOD and industry standards and protocols used for the DIS architecture.

If DIS is to be used to make acquisition decisions, the elements of the network must provide an environment accurate enough that simulation results can be used with confidence. This means verification and validation should be accomplished at the major command level within the Army and accreditation should be at the Army staff level. The U.S. Army Training and Doctrine Command (TRADOC) may provide the combat development requirements and the Army Materiel Command can provide the acquisition requirements to form an accurate and acceptable simulation environment.

The BDS-D plans to link government, industry and academic facilities together using an object-oriented distributed system with standards derived from SIMNET. In Phase I of BDS-D (FY 1992-94) a number of advances over SIMNET capability are planned. See Figure 22. Increased fidelity of the simulation battlefield is required to support acquisition decisions.

ENDNOTES

1. DMSO briefing, "The Expanding Role of Modeling and Simulation in the Acquisition Process," 24 November 1992, p. 7.

2. Zeid. *CAD/CAM Theory and Practice*, p. 12.

3. Foston. *Fundamentals of Computer-Integrated Manufacturing*, p. 21.

4. *Ibid.*

5. "CATIA Data Management and CATIA Data Management Access," p. 1.

6. "Pro/Engineer," p. 2.

7. Zeid, p.927.

8. Foston, p.21.

9. *Ibid*, p.144.

10. Norton. *Design of Machinery*, p. 370.

11. Wilke. "Parametrics Faces Counterattack from Upended Rivals," p. B4.

12. Chevalier. "Group Technology: The Connecting Link to Integration of CAD and CAM," p. 177.

13. Ferguson. *Engineering and the Mind's Eye*, p. 194.

14. *Ibid*, p. 179.

15. Cutkosky, M., et al. "PACT: An Experiment in Integrating Concurrent Engineering Systems," p. 1.

16. 3D-CAM, "Prototypes in the Speed of Light."

17. Carrabine. "Listening for E.T."

18. 3D-CAM, "Prototypes in the Speed of Light," undated.

19. Standard & Poor., "OTC Stock Report," 20 March 1992.

20. DMSO briefing, "The Expanding Role of Modeling and Simulation in the Acquisition Process," 24 November 1992, p. 12.

21. *Ibid.*

22. *Ibid*, p. 7.

23. Briefing, S&T Thrust #6, "Conference on Synthetic Environments: Current and Future Directions," 7 December 1992.

24. *Ibid.*

25. MITRE briefing, "Perspectives on the Use of Modeling & Simulation (M&S) in the Acquisition Process," 1 December 1992.

26. DARPA briefing, "Manufacturing Automation and Design Engineering," 6 October 1992, p. 16.

27. Interview, Mr. Terry Gossett, NASA/Ames, 12 March 1993.

28. "IBM Ventures To Hollywood in Visual Effects," *Wall Street Journal*, 26 February 1993, p. B1.

29. "ONLINE Interview, Dr. Thomas A. Furness III, Virtual Reality Pioneer," p 14.

30. Rheingold. *Virtual Reality*, p. 70.

31. NASA Ames Research Center, "Virtual Interface Environment," 1986, p. 1.

32. "The Marvels of 'Virtual Reality'," *Fortune*, 3 June 1991, p. 1.

33. *Ibid*, p 2.

34. "Virtual Reality Comes Into Focus," *Mechanical Engineering*, April 1991, p. 2.

35. Interview, Mr. Terry Gossett, NASA/Ames, 12 March 1993.

36. Virtual Interface Technology (Virtual Reality) class notes, 15-17 March 1993.

37. "Virtual Reality," *Business Week*, p. 100.

38. Defense Modeling and Simulation Office, "Defense Modeling and Simulation Initiative," 1 May 1992, pp. C-1 - C-15.

39. Defense Modeling and Simulation Office, "Defense Modeling and Simulation Initiative," 1 May 1992, p. 3.

40. Lane. "Fidelity and Validity in Distributed Interactive Simulation: Questions and Answers," p. 4.

41. Interview, Mr. Dennis W. Ruhl, International Business Machines Corporation, 3 February 1993.

42. Interview, Dr. William Bricken, University of Washington, 23 March 1993.

43. Reingold. *Virtual Reality*, p. 81.

44. Virtual Interface Technology (Virtual Reality) class notes, 15-17 March 1993.

45. Reflection Technology, 230 Second Avenue, Waltham, Mass. 02154.

46. Virtual Vision, Inc., 7659 178th Place N.E., Redmond, Wash. 98052.

47. Shiflett. "Simulation in a Changing World — Technological Opportunity, Management Challenge."

X rays are a hoax.
— **Lord Kelvin, ca. 1880**

Chapter 4
SYNTHETIC ENVIRONMENTS IN ACQUISITION

In previous chapters, we summarized the defense acquisition environment and described virtual prototyping tools. This report now presents, in detail, how these tools can be used in defense acquisition. In this chapter, we start with a synopsis of the acquisition process delineated in DOD Directive (DODD) 5000.1 and DOD Instruction (DODI) 5000.2. We identify and discuss the two policy areas where virtual prototyping offers the greatest promise — translating operational needs into stable, affordable programs and acquiring quality products. We then discuss the possible use of advanced simulation in a wide range of applications induding analysis of campaign and force structure, system advocacy, configuration determination, trade-off studies, cost analysis, engineering design support, testing and evaluation, development and operational test design, excursion and sensitivity analysis, and production and logistics. Our purpose is to describe current and potential applications in each of these areas. Our intent is to help program managers (PMs) who want to capitalize on the advantages of advanced simulation to help manage their programs and policy makers attempting to influence the future direction of simulation and virtual prototyping.

THE ACQUISITION PROCESS

To better appreciate th current and potential future impacts of virt prototypes on the acquisition process, the following synopsis from DODD 5000.1/DODI 5000.2 is provided to refresh the reader's awareness of current acquisition policy. Policies not germane to the use or impact of virtual prototypes have not been included in this summary.

Policies and Procedures

The DOD is the largest purchaser of supplies and services in the federal government. In the past, numerous regulations, directives, Service-unique supplements, etc., have been issued to provide guidance to the various DOD acquisition communities. Unfortunately, there was great duplication and often somewhat confusing and conflicting guidance between these numerous documents. Thus, the "acquisition system" became part of the problem instead of a solution to ongoing attempts by DOD to optimize the return for its acquisition dollars. In early 1991, the Deputy Secretary of Defense issued a new directive to attack this problem. The DODD 5000.1, "Defense Acquisition," dated 23 February 1991, replaced the previous version, "Major and Non-Major Defense Acquisition Programs." It also replaced DODD 4245.1, "Military Department Acquisition Management Officials" and canceled more than 60 previously-issued DOD acquisition directives, instructions and memorandums. The stated purpose of the new directive is to establish "a disciplined management approach for acquiring systems and materiel that satisfy the operational user's needs."[1] The new acquisition policies set forth

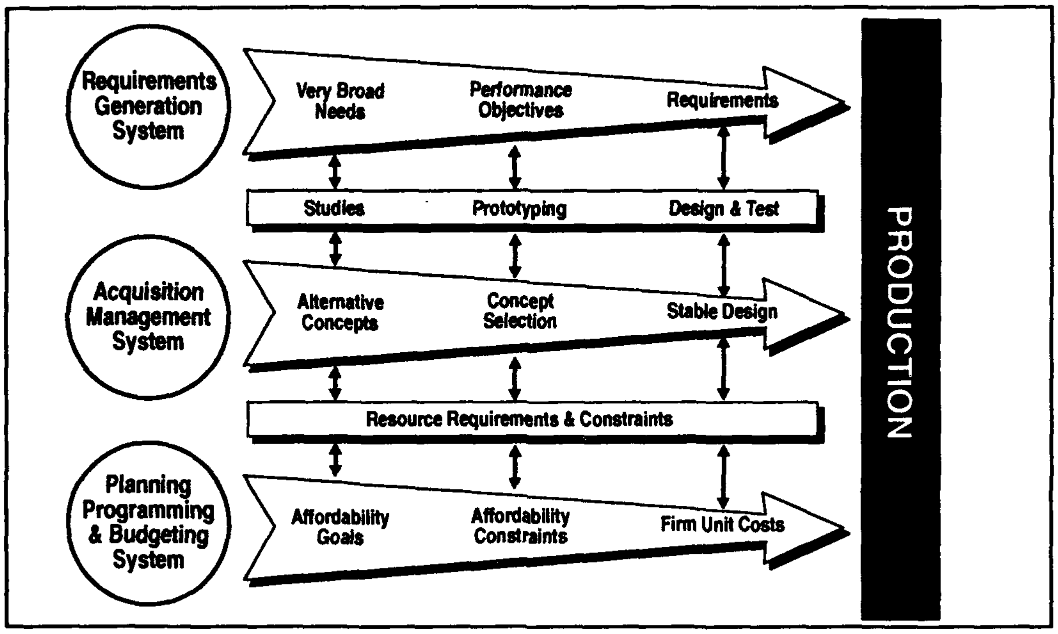


Figure 23. **Key Interactions**

in this document are intended to "establish a disciplined approach for integrating the efforts and products of the DOD's requirements generation; acquisition management; and planning, programming, and budgeting systems."[2] Figure 23 graphically illustrates these key interactions.

This disciplined approach is designed to provide a method to translate operational needs into stable, affordable programs that acquire only quality products. The directive mandated a new streamlined acquisition management structure to be organized for efficiency and effectiveness. It requires PMs assigned to manage major defense acquisition programs to report through Program Executive Officers to the DOD Component Acquisition Executive or directly to the DOD Acquisition Executive, when warranted.

Subjects covered by the more than 60 documents superseded by DODD 5000.1 were consolidated and simultaneously replaced by a new DODI 5000.2, "Defense Acquisition Management Policies and Procedures." This Instruction reissued Instruction 5000.2 and authorized the Under Secretary of Defense (Acquisition and Technology) (USD(A&T)), (formerly the Under Secretary of Defense (Acquisition)) to publish DOD 5000.2-M, "Defense Acquisition Management Documentation and Reports," in accordance with DOD 5025.1-M, "Department of Defense Directive System Procedures." The stated purpose of DODI 5000.2 is to establish:

— An integrated framework for translating broadly stated mission needs into stable, affordable acquisition programs that meet the operational user's needs and can be sustained, given projected resource constraints; and,

— A rigorous, event-oriented management process for acquiring quality products that

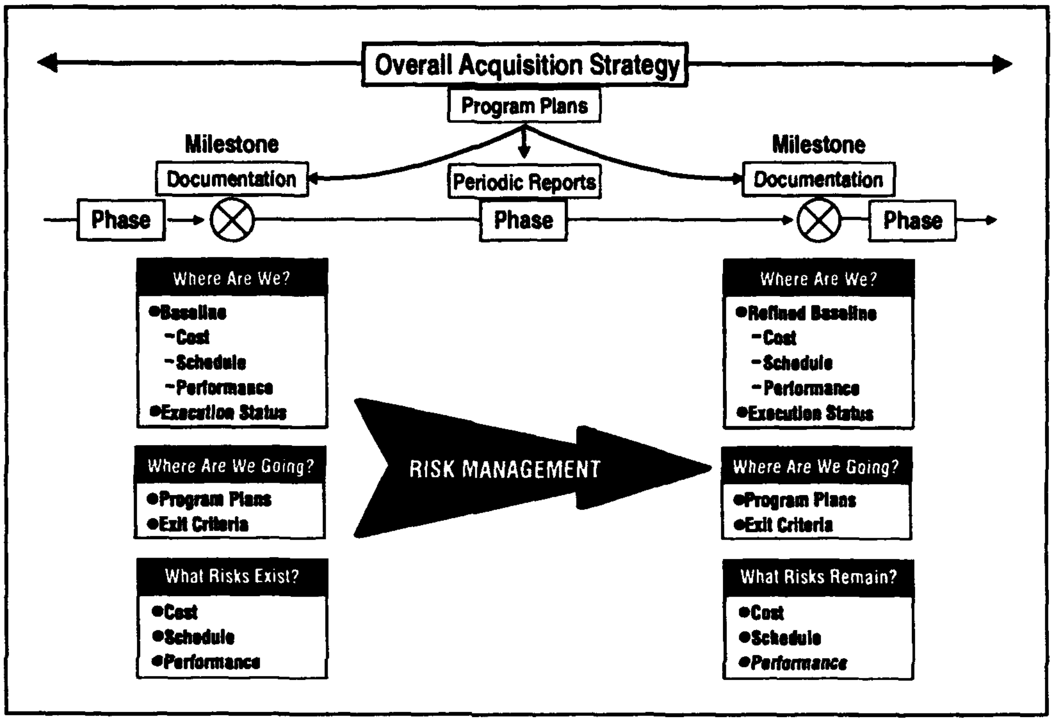


Figure 24. **Acquisition Phases and Milestone Decision Points**

> emphasizes effective acquisition planning, improved communications with users, and aggressive risk management by both government and industry.[3]

By issuing DODD 5000.1 and DODI 5000.2, the DOD has established a core of fundamental policies and procedures that can be implemented down to the PM and field operating command level without supplementation. Increased efficiency and effectiveness will be achieved through an acquisition management structure that has been streamlined by establishing short, clearly defined lines of responsibility, authority and accountability.

From program inception through the fielding process, the PM is required to develop and keep current the acquisition strategy for the program. The acquisition strategy is the overall road map for the program and is reflected in the detailed plans the PM uses for program management. At each milestone (MS) decision point, a synthesis of these program plans, along with the essential information needed to comply with statutorily imposed requirements and make decisions, is provided by the PM to the MS decision authority. The PM must provide the MS decision authority with periodic assessment reports during the execution of the program between MSs. These assessment reports must address the status of program accomplishments against program plans and baselines for that phase of the program. The chart shown in Figure 24 illustrates the over-arching acquisition strategy and the relationship of the program plans, milestone documentation and periodic reports.[4] Requirements documents, the Integrated Program Summary (IPS) with annexes and

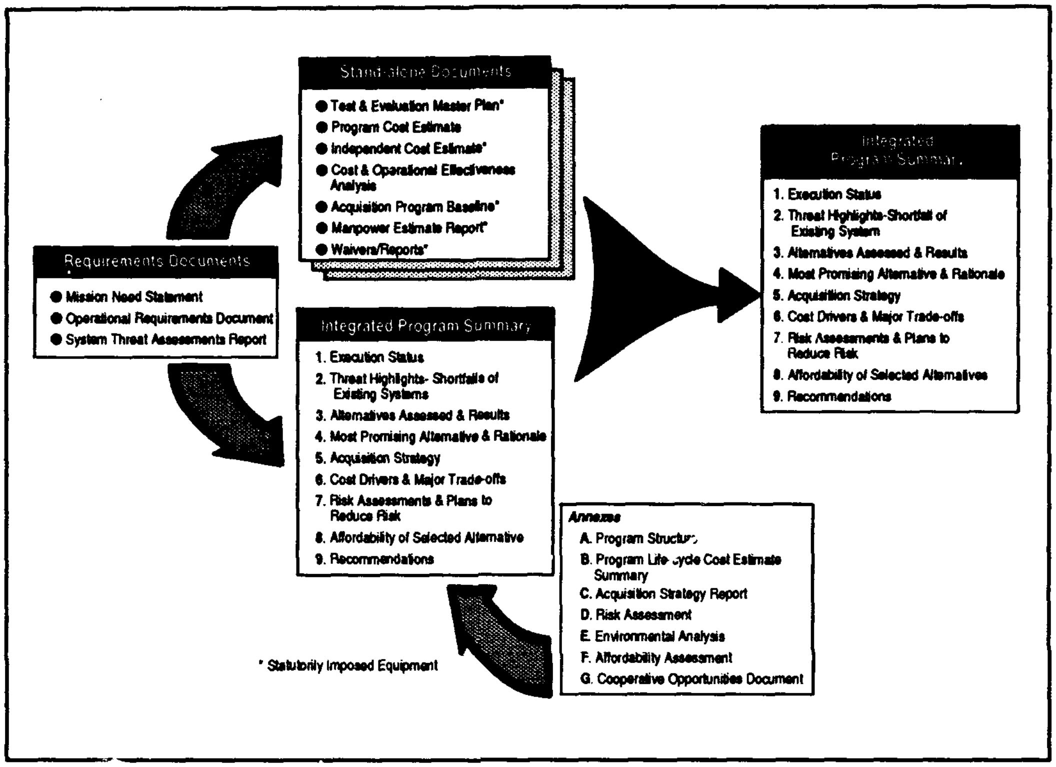


Figure 25. **Milestone Documentation Concept**

stand-alone documents are the three general document categories for an MS review. Information provided in the IPS and stand-alone documents provide the staff with the information needed to develop the Integrated Program Assessment and enable the MS decision authority to make an MS decision. The MS documentation concept in Figure 25 shows the types of information included in each category.

Part 1 of DODD 5000.1 contains acquisition policies designed to provide a means for translating operational needs into stable, affordable programs that acquire quality products. The following two sections contain policies from DODD 5000.1 that are key to understanding the subject of this report.[5]

TRANSLATING OPERATIONAL NEEDS

Evolutionary Requirements Definition

Mission needs must be expressed by the user community in broad operational capability terms, and nonmateriel solutions such as a change in doctrine must be considered before proceeding with an acquisition program.[6] Figure 26 provides an overview of the steps involved in processing a Mission Need Statement (MNS).

The Joint Requirements Oversight Council decides if the mission cannot be satisfied by a nonmateriel solution, "validates" the need, assigns a joint priority, and forwards it to the USD(A&T). The Under Secretary convenes a Defense Acq[illegible]n Board (DAB) to review the MNS. T[illegible]w and decision point is

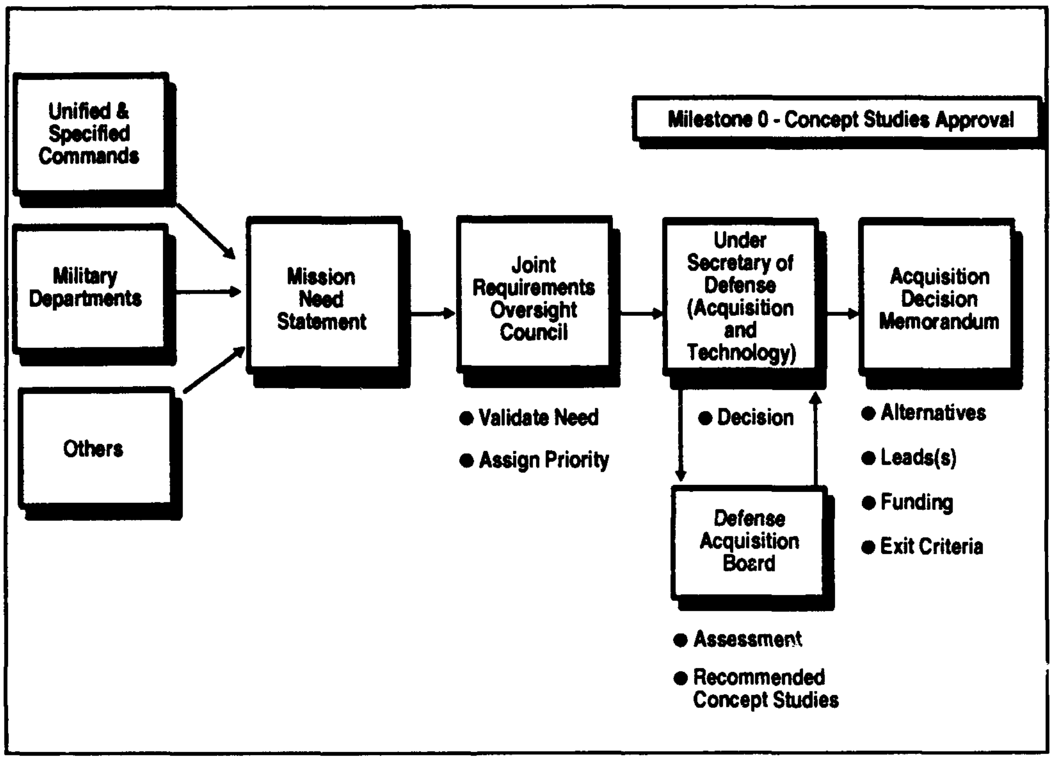


Figure 26. **Mission Need Statement Flow**

called Milestone 0, Concept Stu[illegible] pproval, and it establishes the initial int[illegible] between the requirements generation an[illegible] acquisition system. Favorable action by the DAB is documented by an Acquisition Decision Memorandum that:

— Directs studies of a minimum set of materiel alternatives;

— Designates a lead department or agency to conduct the studies and present the results at the next milestone review; and,

— Identifies a source of funds for the studies.[7]

MILESTONES AND PHASES

The acquisition process is structured in discrete, logical phases, separated by major decision points or MSs.[8] As Figure 27 indicates, there are five major MS decision points and five distinct phases in the acquisition process.

The sequential process indicated by the diagram provides a basis for comprehensive management and supports the progressive decision making process associated with program maturation.[9]

Major considerations at each decision point shall include threat projections, life-cycle costs, cost-performance-schedule trade-offs, affordability constraints, and risk management. Acquisition program MS decision authority shall be delegated to the lowest level deemed appropriate by the USD(A&T) or the DOD Component Head, as appropriate.[10]

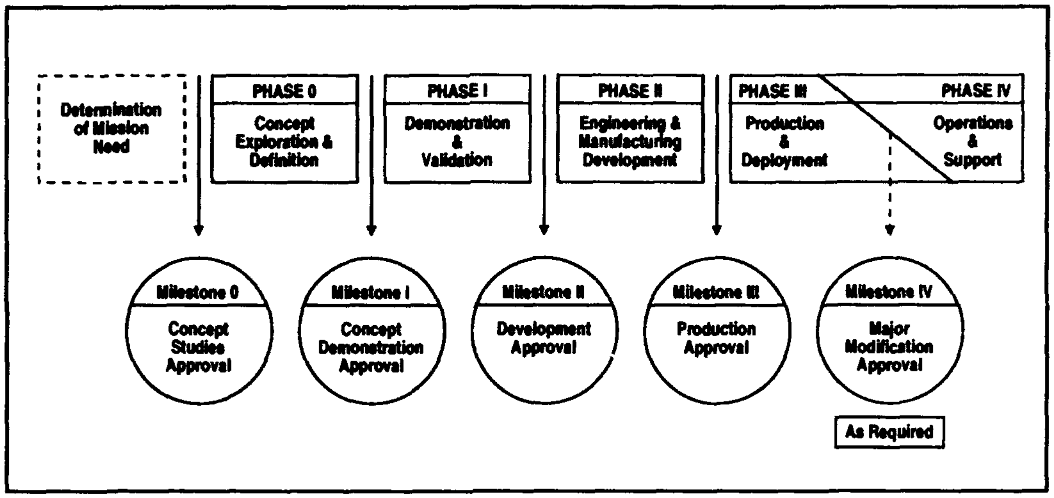


Figure 27. **Aquisition Milestones and Phases**

At MS I, Concept Demonstration Approval, the results of the studies are evaluated and the acquisition strategy and proposed concept in terms of cost, schedule and performance objectives are weighed against projected funding availability.

Approval at MS I marks the start of a new acquisition program. Once a "new start" has been approved, the broad operational capability requirements must progressively evolve to system-specific performance requirements such as speed, range, payload, etc. Validated intelligence threat assessments must be used to ensure the system being developed is mission capable in its intended operational environment.[11] Figure 28 depicts the evolutionary requirements definition process and its relationship to the requirements generation and acquisition management systems.[12]

ACQUIRING QUALITY PRODUCTS

To acquire quality products, effective acquisition planning and aggressive risk management by government and industry are essential for success. Program decisions and resource commitments must be based on plans for, and progress in, controlling risk.

Acquisition Strategies, Exit Criteria and Risk Management

Primary in developing an acquisition strategy is minimizing the time it takes to satisfy an identified need consistent with common sense, sound business practice, and the provisions of DODD 5000.1 and DODI 5000.2. The number of phases and decision points must be tailored to meet the specific needs of individual programs. The tailoring must be based on an objective assessment of a program's status, risks, and the adequacy of proposed risk management plans.[13] Acquisition strategies and program plans will be event-driven and explicitly link major contractual commitments and MS decisions to demonstrated accomplishments in development, testing and initial production. At each MS decision point, assessments will be made of the status of program execution and the plans for the next phase and the remainder of the program. Program specific results to be required in the next phase, called exit criteria, are also established.

Exit criteria are critical results that can be viewed as gates through which a program must pass during the phase. Two examples of exit criteria are:[14]

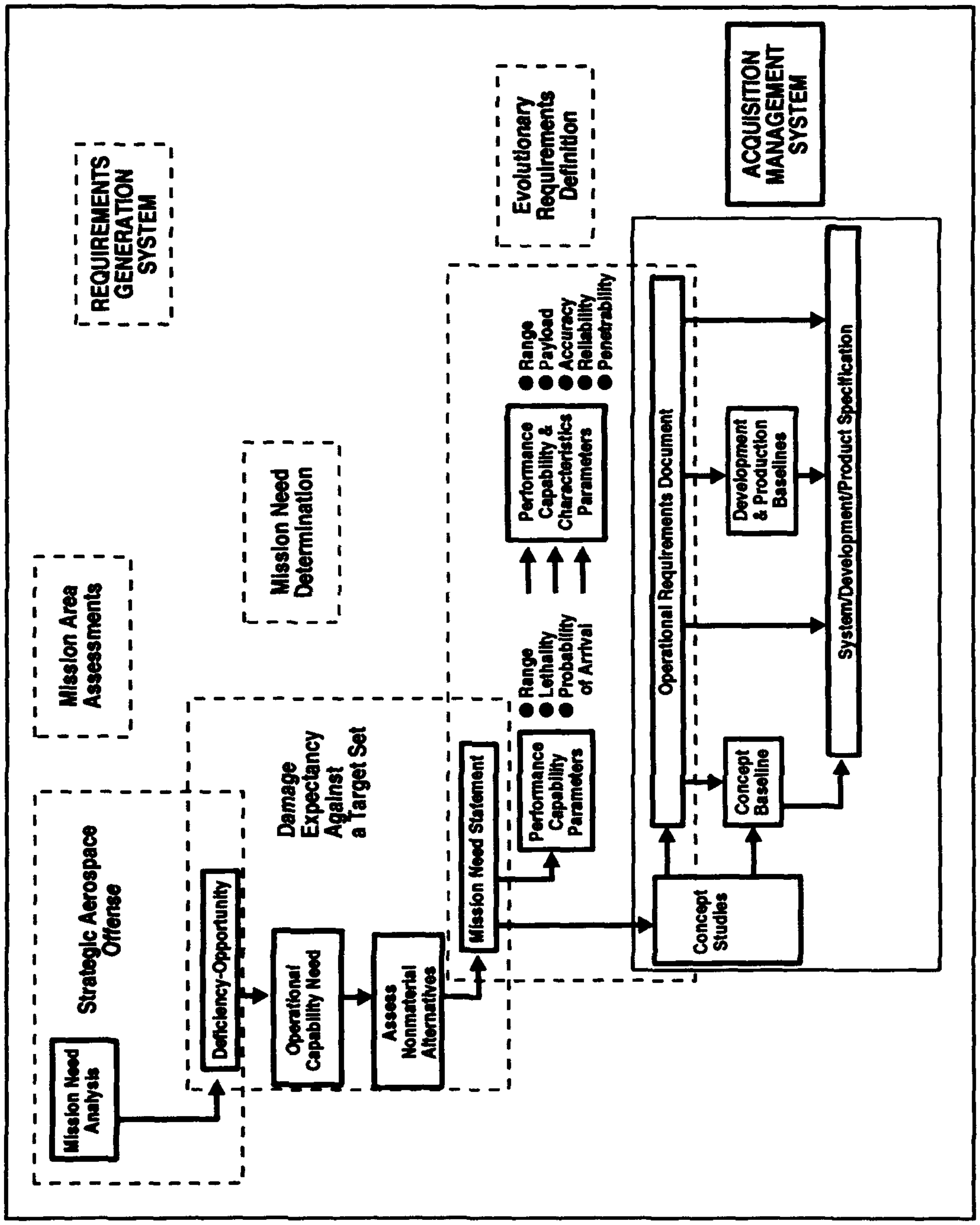


Figure 28. **Evolutionary Definition Requirements Process**

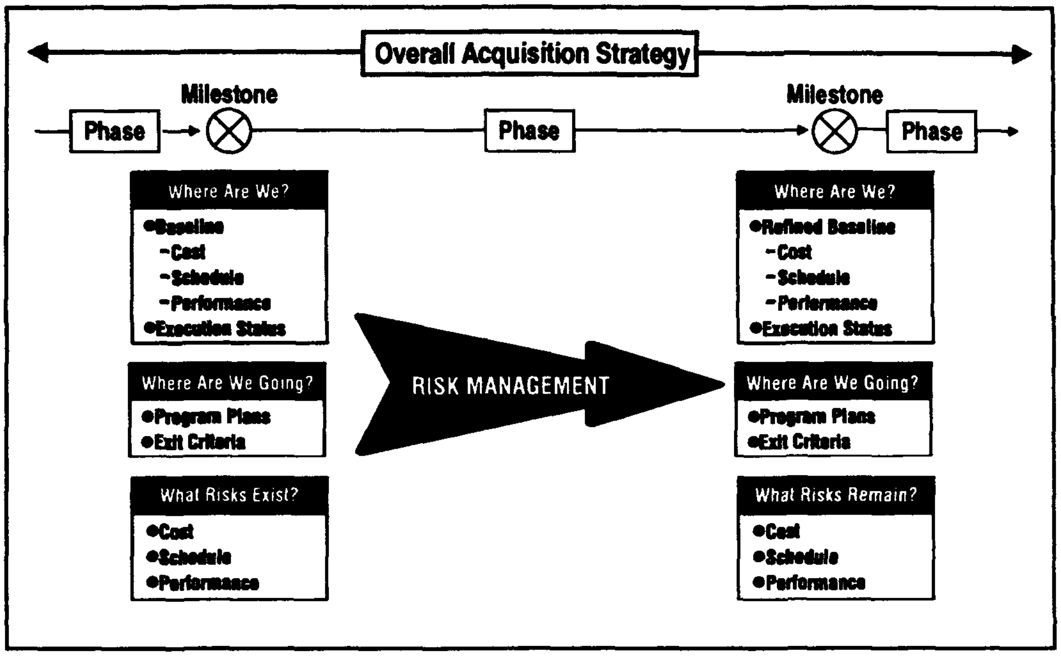


Figure 29. **Acquisition Phases and Milestone Decision Points**

— Achieve a specified level of performance in testing or conduct a critical design review prior to committing funds for long lead item procurement.

— Demonstrate the adequacy of a new manufacturing process prior to entry into low-rate initial production.

Program plans provide for a systems engineering approach to the simultaneous design of the product and its associated manufacturing, test and support processes. This concurrent engineering approach is essential to achieving a careful balance among system design requirements such as operational performance, producibility, reliability, logistics and human engineering.[15]

The DODI 5000.2, Part 6, sets forth a group of policies and procedures establishing a common frame of reference for developing plans in engineering and manufacturing. Systems engineering, reliability and maintainability, transportability, human factors, computer-aided acquisition and logistics support (CALS), and design for manufacturing and production are all areas that could be affected by virtual prototypes.

Program risk must be explicitly assessed at each MS decision point before granting approval to proceed to the next acquisition phase. Figure 29 illustrates this process.

Critical parameters that are design cost drivers or have a significant impact on readiness, capability and life-cycle costs must be identified early and managed intensively. Technology demonstrations and aggressive prototyping (including manufacturing processes, hardware and software systems and critical subsystems), coupled with early operational assessments, are to be used to reduce risk.

Determination of system maturity and identification of technical risk areas is accomplished through test and evaluation. Requests for Proposal require contractors to identify areas of risk and provide specific plans to assess and eliminate risks or reduce them to acceptable levels. At each MS decision point, the following risk areas must be assessed:[16]

— Threat, technology, design and engineering, support, manufacturing, cost and schedule

— Risks inherent in the proposed degree of concurrency.

Program Objectives and Baselines

At the new start, MS decision broad objectives for cost, schedule and performance parameters are established. These parameters are reviewed and refined at each subsequent MS decision and are the basis for the program baselines. The selected performance objectives must satisfy operational needs specified by the user and must be verifiable by testing.[17] In the following discussion, we examine the use of virtual prototypes and how they might impact the attainment of cost, schedule and performance parameters. The discussion is segregated into the five functional subgroups involved in the acquisition process.

ANALYSIS

The collapse of the Soviet Union eliminated the threat of a large-scale struggle for national survival. As a result, our defense and acquisition strategies have been revised to focus on a world that may erupt in one or more regional conflicts. Strategic deterrence is still important but force structure must be changed to accommodate the increased emphasis on power projection necessary to adequately address the wide spectrum of options required in regional conflicts.

Civilian evacuation, surgical strikes, peacekeeping activities, forcible entry up to and including full-scale war are examples of the wide range of scenarios facing our military services.

The new DOD acquisition strategy establishes the framework for continuously demonstrating technology to provide technology options for force planners and defense decision makers. If the new capability (component, subsystem, system, etc.) successfully influences the outcome of the mission, a decision will be made to either upgrade existing systems through incorporation of the technology or to begin development of an entirely new system based on this new capability. But how do we demonstrate new capabilities when the force structure and the DOD acquisition budget are being reduced dramatically? Breakthroughs in advanced simulation technology have the potential to allow DOD to accomplish this challenging task and to improve weapon system procurement dramatically. The following sections address using virtual prototypes in synthetic environments for campaign analysis and force structure assessment.

Campaign Analysis

Campaign analysis involves evaluating the interaction of one or more large friendly forces and an enemy force. Emphasis is on enhancing the adequacy of the models used in campaign analysis to better represent the conduct of joint and combined operations. A 1988 Army Science Board report states:

> Wargame models are best used in broad identification of issues and development of insights. Wargame models...should not be used for the evaluation of alternative solutions or sensitivity analyses.

The report further recommended replacing the assessment routines in training models with those used in analysis models. The data used in these assessment routines, to the maximum extent possible, should be measur-

able data generated by Army and Air Force laboratories. According to the Science Board, major disparities exist in the assumptions, employment logic and assessment routines used by the Services in their respective campaign models and a program should be developed to resolve these differences.[18]

As discussed in this report, realistic virtual prototypes with man-in-the-loop operation have been developed for individual weapon systems. Multiples of certain prototypes have been electronically coupled to allow battlefield scenarios participation in limited size and duration. Because campaign analysis usually involves the interaction of large forces over extended periods of time, the modeling done for one item of equipment (one M-1 tank, F-16 aircraft, etc.) within the overall force structure is usually limited, if modeled at all. A single strategic platform may involve more extensive modeling but even this effort is not one that includes an operator-in-the-loop during the exercise of the model. Because of the nature of campaign analysis, it does not seem the use of a manned virtual prototype would have any benefit. Modeling and simulation in general, however, have an application in campaign analysis. Future expectation is campaign analysis models will be able to furnish senior defense officials with a tool for budget deliberations relating individual system effectiveness to the predicted outcome of military campaigns.[19] We had no opportunity to research this specific type of analysis; thus, our assessment may warrant further review.

Force Structure Assessment

Warfighting concepts to meet changing world realities are in a period of reassessment. A specific threat is no longer the basis for an acquisition requirement. The DOD is focusing on capabilities and how each might influence the outcome of a specific scenario (regional conflict in Country X, surgical strike in Country Y). A key part of each evaluation is the size and skill level of the force structure required to accomplish each mission. Synthetic environments employing different weapon systems and different force structures permit DOD war planners and higher level decision makers to evaluate the impact of changing the types and numbers of weapon systems and their respective crews and support structures. Inherent in these ongoing synthetic force-on-force evaluations is the opportunity to insert a new capability via a virtual prototype and evaluate its impact. The virtual prototype can be represented at any hardware level in the evaluation; i.e., a new radar in an existing fighter or helicopter, a new missile mounted on a tank, or a totally new weapon concept. If the new capability provides a significant force multiplier to the unit, reducing unit size or numbers may be possible while maintaining an acceptable level of combat performance. *Similarly, virtual prototypes can facilitate* operator workload assessments associated with the introduction of a new capability. If the new integrated sensor suite being evaluated involves extensive automation and little or no operator input, perhaps a smaller crew can operate the new weapon system platform. Alternatively, because of reduced workload, the original crew can now execute its mission more effectively (identify and kill more targets) and, thus, fewer weapon systems are required. The Army used a virtual prototype of the Comanche built by Sikorsky for assistance in confirming the proper crew size and respective functional assignments within the cockpit.[20] The "electronic battlefield" created via distributed interactive simulation will allow DOD decision makers to evaluate weapon systems and force structures on an interactive basis to determine the optimum mix for future conflicts.

SYSTEM ADVOCACY

In the early stages of any new weapon system development, the user and the developer are

confronted with a problem — how to develop a constituency willing to support and fund the new system. The sphere of system advocacy must be expanded from its initial set of users and developers to the larger Service and congressional environment. For example, the aviation community may have to convince the armor community that a new helicopter is *the* most critical component for a combined arms team. In the past, each weapon system proponent based the *need* for a new system on the evolving capabilities of a similar threat system. Since the DOD budget in the 1980s was sufficient to permit an aviation development *and* an armor development at the same time, the "advocacy" issue was usually limited to one where other functional areas acknowledged and agreed the new system had merit. Obviously, each Service had to justify its programs in the annual budget battle and provide support to DOD in justifying its budget to Congress. System advocacy was normally developed through a continuing series of individual Service and contractor briefings. Color viewgraphs and artists concepts were the primary means of visualizing the new weapon system at these sessions and rarely did they address the capabilities of other new systems.

Those days are gone! As described in Chapter 2, the DOD budget has been dramatically reduced and these reductions will continue in the foreseeable future. Each Service is "downsizing" in accordance with the FY 1993 guidance and, at the same time, internal and external reviews are being conducted to determine if the roles and missions of each Service (per the 1947 Key West agreement) are still valid. The primary thrust is to reduce any overlap of capability among the Services; the obvious goal is to further reduce equipment and manpower. In this new lean environment, obtaining system advocacy has taken on a much broader and potentially more crucial meaning. The system proponent must now convince its functional area constituents and attempt also to establish in the same Service at least a neutral ground with other functional areas competing for their share of an ever-decreasing budget. This competition for funds is best characterized as survival of the fittest and advocacy of the system by components other than the developer is essential in today's environment. The ability to demonstrate the "value-added" capabilities of a new system while at the same time convincing the audience the technical and financial risks associated with obtaining this capability are reasonable is essential in this multilayered funds competition. Many skills associated with professional marketing are becoming an essential ingredient in this new environment.

Basic marketing research indicates that gaining support for a new product is facilitated by pictures of the item and more so by a sample or model. Our research has indicated the use of a virtual prototype can positively influence product support (system advocacy in DOD terminology) at all levels of the acquisition process. Because of the benefits of 3-D visualization, the virtual prototype facilitates introduction of a new weapon system concept and increases user involvement in the development process by providing a better means for earlier and more productive user and developer communication. High user interest is maintained primarily because the virtual prototype can accommodate rapidly incorporating suggested user changes to the design. The ability to evaluate multiple options with the user community is key to developing a user sense of ownership which is essential for system advocacy. The same 3-D visualization portrayed to the user is a primary ingredient in building system advocacy throughout the acquisition community. Having a virtual prototype available to demonstrate to technical and budgetary decision makers has tremendous potential for assisting the developer in convincing the audience that program risk is

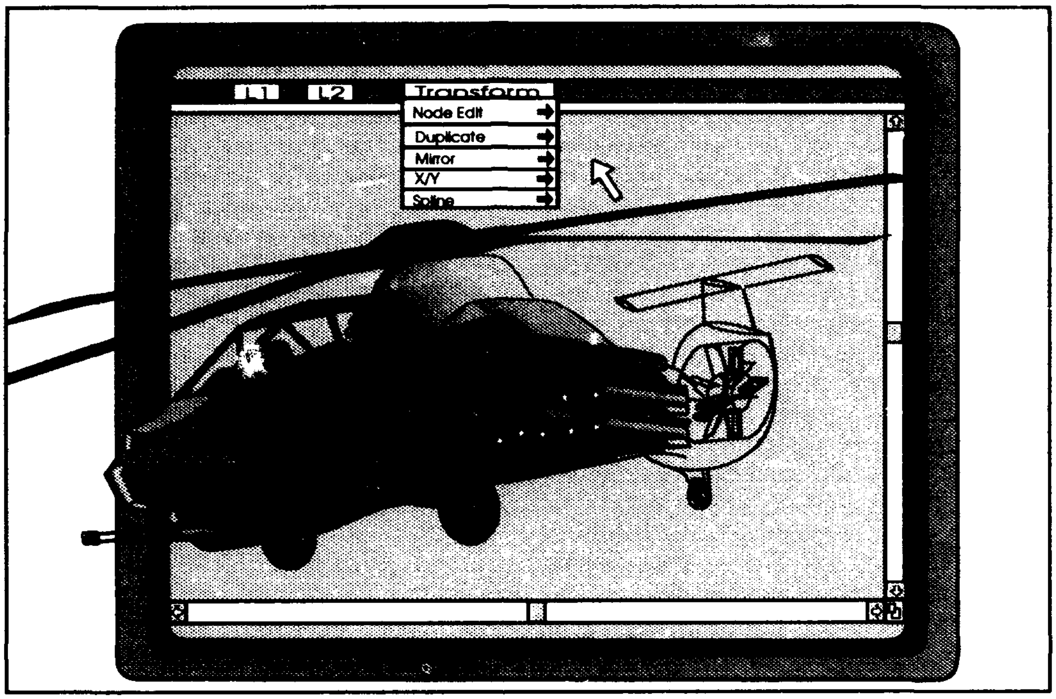


Figure 30. **Artist Visualization of RAH-66 Comanche Virtual Prototype**

being reduced. This is especially true for virtual prototypes produced on computer systems that are coupled to the computer-based engineering drawing and manufacturing systems. A digital model that can be rotated and examined from all angles, including a view from the inside, is more believable than a three-foot stack of viewgraphs containing 2-D drawings. Figures 30, 31 and 32 are examples of virtual prototypes developed for Army, Air Force and Navy programs. They illustrate graphically the power of 3-D visualization.

The Boeing Sikorsky RAH-66 Comanche team has made extensive use of its virtual prototype in winning the Army's newest and largest aviation program. System advocacy was enhanced by better user interface with the contractor design team and active Army test pilots actually *flew* the virtual prototype during the Concept Development Phase of the program. Insights gained from these flights coupled with other contractual information have permitted the Army to down select to one source for the follow-on Engineering and Manufacturing Development Phase of the program.

The Electric Boat Division of General Dynamics also is using their virtual prototype of the next generation submarine, the Centurion, to build system advocacy during the infancy of this emerging program. As illustrated by Figure 31, the ability to graphically represent their concept in a computer generated 3-D solid model is a powerful marketing and design tool. Development of system advocacy will certainly be facilitated by Electric Boat's capability to allow future users as well as DOD and congressional decision makers to "walk through" the new Centurion and thus gain a multidimensional appreciation for the

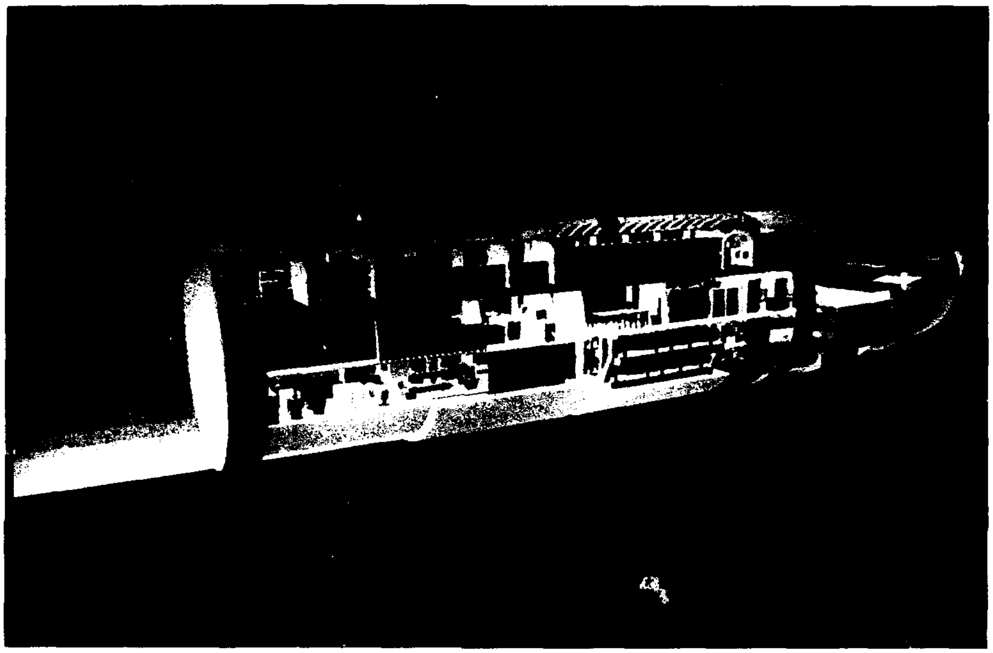


Figure 31. **Computer-Generated 3-D Model of Centurion Submarine Protoype**

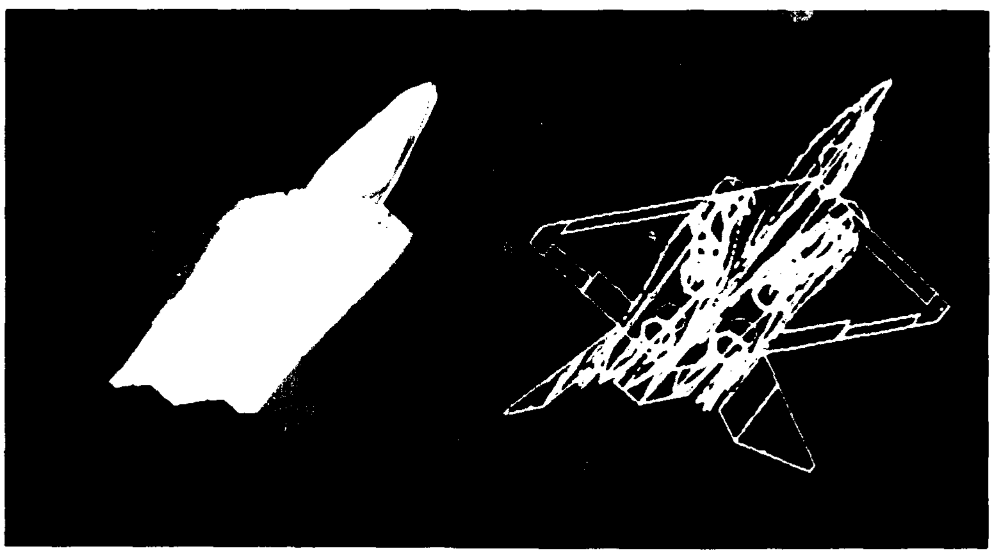


Figure 32. **F-22 Aircraft Prototype**

Figure 33. **TRW's Design for Brilliant Eyes Satellite**

viability of their concept. During our visit to their facility we were given the opportunity to experience their visualization techniques and facilities. As hard as it may seem, three officers from non-Navy Services began to believe in their approach.

Virtual prototypes are being used by Boeing on both Air Force and commercial programs. Figure 32 is a model of the new F-22 being developed utilizing this process. The dimensions from the virtual prototype have been electronically transferred to a stereo lithography machine that produced this scale model.

Boeing also has made the corporate decision to use virtual prototypes in commercial aircraft design and fabrication. The world's largest builder of aircraft believes this technology will enable them to develop the necessary system advocacy among their commercial customers to remain number one in the 21st century. Today, they use their virtual prototype in the design and fabrication of their next generation wide-body aircraft, the Boeing 777. No physical prototype will be built on this program and the tools and jigs will be fabricated based on information from the virtual prototype.[21]

The long-term goal for future utilizations of virtual prototypes is to permit the electronic transfer of prototype information directly into manufacturing machines in a manner where the parts can be created with little or no human intervention.

Based on our discussions with personnel at the TRW Engineering Visualization Center, animated 3-D models are becoming the "marketing essential" in the initial stages of winning a contract, and TRW believes it gives them the "perceptual edge" in presenting advanced technical concepts and system de-

signs. Figure 33 is a 3-D animation of a new TRW space system depicting the engineering staff working on the virtual integration of the TRW design for Brilliant Eyes satellites.

The TRW program managers are convinced that virtual prototypes give them the marketing advantage with potential customers. The ability to use animated graphics to present data visually is especially valuable where patterns are difficult to discern. The development of an interactive program that permits the potential customer to manipulate antenna aim-point and hand-over time and see the resulting changes in Earth coverage immediately, rather than in a batch mode, gives them a competitive edge.[22]

As the difficulty of conducting business in the DOD marketplace continues, earliest establishment of system advocacy will become even more important. Fewer and fewer programs will be authorized as a "new start" and anything assisting a PM (government or contractor) in gaining a competitive edge will become necessary for survival. Having a virtual prototype may provide the deciding edge in obtaining system advocacy in the future.

Because the prototype is "virtual," it can be used also to gain system advocacy through electronic participation in the DOD "electronic battlefield." These demonstrations and evaluations are being conducted by the Defense Modeling and Simulation Office (DMSO) and the Advanced Research Projects Agency (ARPA).

This capability was introduced to Senate Armed Services Committee members by a live demonstration in their hearing room in May 1992. Based on the demonstrated impacts to date, the development of a virtual prototype may rapidly become the single most important ingredient in system advocacy development.

SYSTEM CONFIGURATION DETERMINATION

One of the more challenging tasks facing the DOD program manager is persuading the user community to formally describe, adequately and accurately, the real requirement for the system as it makes its way through the acquisition cycle. An even more difficult task, however, is convincing the same user to agree on the one system configuration best able to meet the user's needs, that somewhat more subtle and amorphous term each PM feels he has an obligation to strive to meet because it has a direct impact on the all-important intangible known as system advocacy — sometimes referred to as customer and user "goodwill." Every PM wants the user on his side throughout the development process and to maintain this allegiance will accept numerous changes and endure endless philosophical discussions.

Unfortunately, although the Services attempt to identify a single user representative for purposes of requirements definition and contractor system configuration determination, the actual accomplishment of this goal a single spokesman and decision maker is rarely achieved. Army PMs have formally appointed user representatives called systems managers to whom they can turn for a central point of contact, but even this formal structure has its coordination challenges. In numerous programs, the user is actually an amalgamation of individuals and agencies from throughout the user community and each has the desire, as a minimum, to review and recommend changes to the emerging configuration based on their prior experiences. In addition, the PM is faced with the opportunity to receive input from all the various specialties within the development community. Each wants to assist the PM in determining the optimum system configuration and the PM must attempt to accommodate a great deal of constantly changing input from this

multilayered hydra in order to achieve consensus and move forward with the design.

What does a PM do? In order to facilitate the timely receipt of such advice, most PMs hold periodic program reviews with the contractor and representatives from the user and developer community. If this is an initial meeting following contract award, the contractor's description of the proposed system may be limited to a review using overhead viewgraphs of sketches contained in the proposal plus any subsequent 2-D drawings that may have been created since the award. At sessions such as the Preliminary Design Review and the Critical Design Review, major efforts will be made by the contractor to explain his design and, where possible, obtain feedback from the user and developer community on the acceptability of his approach. Contractors have found these meetings can be a challenging experience and, because of difficulty in describing their system via a 2-D medium, most will construct a physical mockup as a visualization aid in order to maximize the amount of user and developer input received. Depending on the maturity of the system being represented, these mockups can become a significant resource and time-consuming investment.

With the aid of silk screens and Velcro to facilitate subsystem and component relocations, the physical mock-up can be a productive vehicle in the discussion of varying system configurations. This works well until suggestions are made involving changes to silk screens that cannot be made immediately or cannot be implemented readily with available materials. Usually, an agreement will be made to address these suggestions at a later date (tomorrow, next week, next review, etc.). Even if the user has agreed on the subsystem silkscreen location in the mock-up, an engineer then must translate this physical position into the appropriate system level drawings. Once this update has been accomplished, each contributor wants the opportunity to review these drawings to ensure their contribution has been documented properly. A time delay in accomplishing this update is possible; thus, approvals cannot be obtained during the onsite review, and the drawings must be mailed to all parties concerned. Once off-site, the review process can become an opportunity for the contributor to not only review the drawing for accuracy but recommend additional changes based on subsequent deliberations or discussions with other parties in the office or command. Soon, a vicious cycle has been created by the introduction of new changes that need to be approved by multiple parties. Suppose this process could be optimized to permit near-real-time evaluation of multiple recommendations while simultaneously maintaining the necessary information to create all required drawings once a consensus had been reached. Utilizing the visualization techniques existing today, virtual prototypes can assist the contractor and the government PM in accomplishing this task. This was confirmed during our visit to the Electric Boat Division of General Dynamics. As might be expected, Electric Boat has been expanding their utilization of computer-based designs to reduce design and manufacturing costs and remain competitive. They are using these capabilities in many innovative ways, one of which is system configuration determination.

After a general overview briefing on their virtual prototyping capabilities, we received a live demonstration of a virtual prototype in their visualization facility. The virtual prototype demonstrated had recently been used with a Navy customer to determine the system configuration of an accelerated modification the user wanted implemented on a vessel scheduled to make a time-sensitive port call. Because of a limited time frame to gain customer configuration approval, General Dynamics elected to use their new virtual

prototyping capability to accelerate what would normally be a lengthy iterative process to finalize the system configuration. Outside dimensions of the virtual prototype were based on the physical space available on the vessel to accept the desired modification. The information included the location and size of existing doors, pipes, electrical lines, etc. With these dimensions as prototype boundaries, the Electric Boat team used their workstations to develop digital 3-D solid models of the various pieces of hardware the customer desired. These individual digital hardware models were then used with the model of the area to create an all-encompassing virtual prototype that represented the portion of the ship where the installation was to be made as well as the initial equipment layout for the installed hardware. This electronic prototype was then used with customer representatives to determine the system configuration in the same manner as a wooden mock-up. The visualization system allowed the observer to open the door to the modification area, check for clearances with the desk chair and hardware racks, and then move forward and sit at the desk. The virtual prototype included a dimensionally correct representation of a human operator, and the model could graphically illustrate the operators field of view for checking display placement and other hardware the operator needed to be able to see from the chair. During internal and external reviews with their customer, numerous hardware locations were evaluated via the virtual prototype and several significant physical interferences were identified and corrected prior to the sta. ' of construction. Examples of these types of problems were illustrated and we, like the Navy customer, were able to *enter* the model as well as navigate through its dimensionally correct representation. Once customer agreement on the configuration was reached, Electric Boat created the top level layout drawings needed for formal concurrence almost immediately since the modeling process used in the visualization had been based on CATIA drawings. The General Dynamics briefer stated that, based on this virtual prototype information, the modification had been accomplished with an usually low number of in-process changes, within the original schedule and to the satisfaction of the Navy customer. This capability has great potential which PMs should insist be implemented on any new major acquisition.

SYSTEM TRADE-OFF STUDIES

The DOD is faced continuously with choosing between competing alternatives to accomplish a goal. Because the alternatives being considered are normally multifaceted and complex in nature, the DOD employs a process of system trade-off studies to help decision makers evaluate the various options that will accomplish the desired objective at the lowest cost.

At a lower acquisition management level, the PM often is confronted with the same challenge within his own system. He must decide whether to incorporate an accurate and expensive guidance subsystem in his new mobile missile system that allows a smaller warhead to be used to obtain a specified target kill percentage, or he can use a less-accurate and less-expensive guidance system with a larger warhead to achieve the same level of effectiveness. In order to arrive at the most effective solution for a specific need, the decision maker will most likely utilize some type of systems analysis approach to help evaluate the available alternatives. In the missile example, the model may contain key variables such as total system accuracy, warhead lethality and target vulnerability. Figure 34 depicts these target destruction submodel factors.

The first trade-off analysis that would probably be considered involves the division of re-

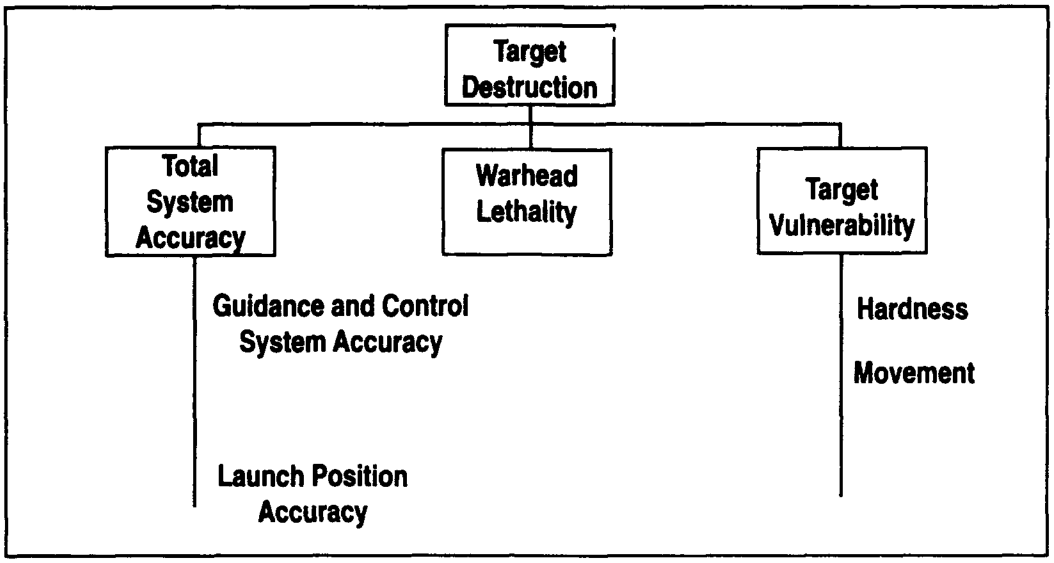


Figure 34. **Target Destruction Submodel Factors**

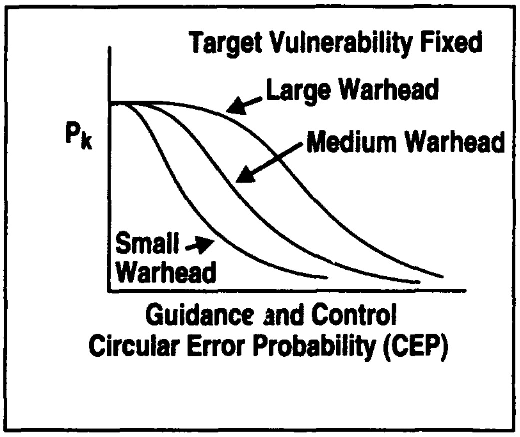


Figure 35. **Target Destruction for Varying Accuracy and Warhead Performance Characteristics**

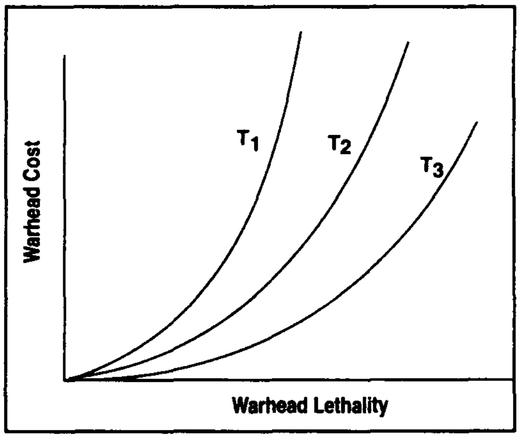


Figure 36. **Performance-Cost Transfer Function for Different Warhead Technologies**

sources between the missile warhead and the missile guidance and control system. It assumes a fixed target of a given hardness and zero error in target position and launch position information. Plotted in Figure 35 are probability of kill curves based on various combinations of warhead accuracy and warhead lethality.

Figures 36 and 37 represent performance-cost functions for different technological approaches. Based on this data, the trade-off be-

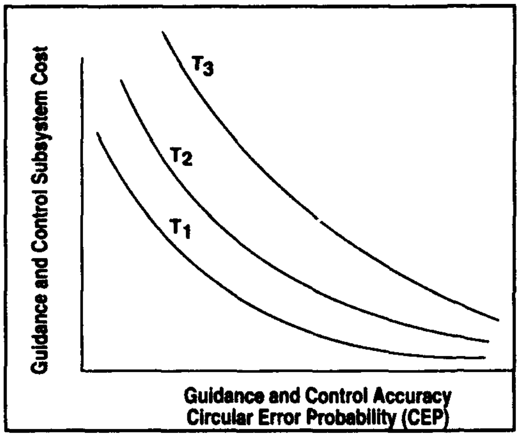


Figure 37. **Performance-Cost Transfer Function for Guidance Technologies**

tween the cost of warhead lethality and missile accuracy can be derived. As shown in Figure 38, the plots represent the most efficient (lowest cost), technologically feasible way for achieving each level of kill probability.[23]

As mentioned, there are always assumptions involved in trade-off analysis and the analyst attempts to address the effects of any potential errors in such assumptions. Deterministic models have specific relationships that will always produce the same answer when the same data is utilized in the equation, regardless of how many times the model is used.

Probabilistic models, on the other hand, have some probability distribution associated with the equations contained in the model and can produce somewhat different results each time the model is exercised. Both types of models, however, are closed and thus do not fully account for the unpredictability of human beings and their impact on the system under

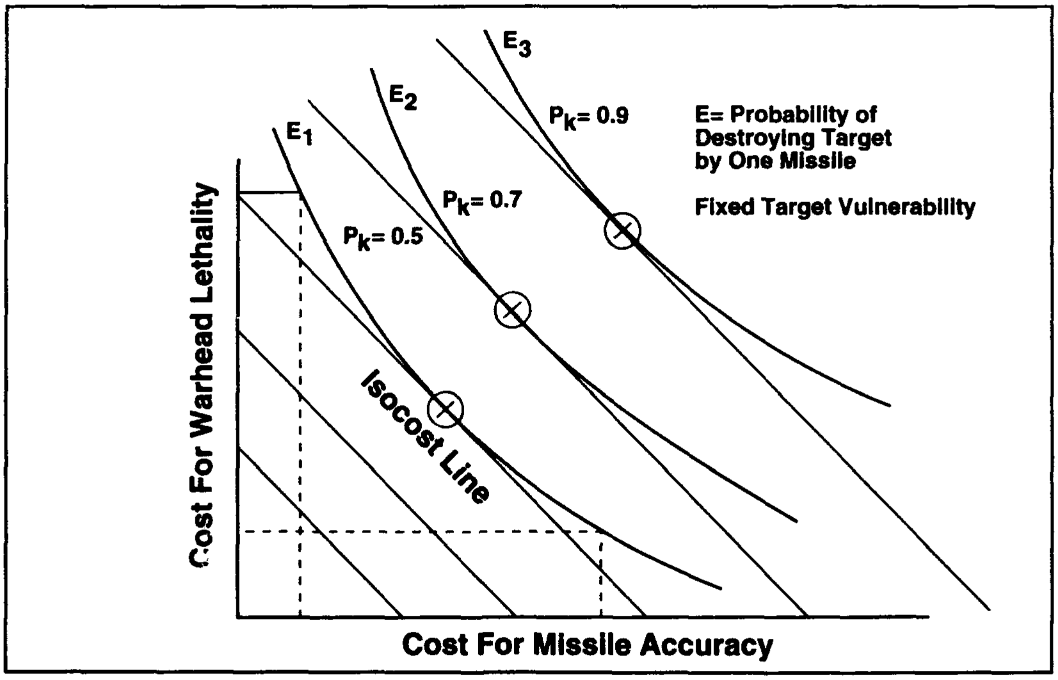


Figure 38. **Isoeffectiveness and Isocost Relationships for Achieving Target Destruction**

evaluation. Introducing a virtual prototype, that is interactive based on real-time operator input in a systems trade-off study, would allow the analyst to expand his ability to collect realistic *total* system level performance data for use in the trade-off analysis. More important, it would enable the engineers to visualize, maybe for the first time, the interactive results of what previously has been 2-D tables of data and thousands of complicated equations. Adding the human element to any previously closed model scenario has the potential to produce unexpected results. As evidenced by the following statement made during Desert Storm by General H. Norman Schwarzkopf:[24]

> *Analysts write about war as if it is a ballet, like it's choreographed ahead of time and when the orchestra strikes up and starts playing, everyone goes out there and plays a set piece. What I always say to those folks is, 'Yes, it's choreographed, and what happens is the orchestra starts playing and some SOB climbs out of the orchestra pit with a bayonet and starts chasing you around the stage and the choreography goes right out the window.'*

The ultimate trade-off study environment envisioned by DOD is still a few years off. It will be based on a totally interactive "electronic battlefield" that contains accurate terrain data and variable weather parameters. It will be populated via distributed simulation with realistic virtual weapon systems that respond to real-time inputs from real operators, and the semiautomated forces will be under the command of real commanders. With this electronic capability as the "test track" for evaluation of new technology, trade-off studies will take on a whole new meaning. No longer will the analytical process described above be enough for a decision. Each system will have to prove itself on this new sand table of the future. The ultimate test will be to demonstrate value-added war fighting capability that is significant enough to influence the outcome of the conflict that takes place in the specified battlespace. Proposed new tanks will be evaluated not only against existing tanks but against other potential weapon system solutions such as attack helicopters, attack aircraft, robotic high energy-weapons, etc. For the first time the decision maker will be able to assess via real-time visualization the warfighting impact of a proposed weapon system before expending several hundred million or billion dollars to develop the first physical prototype.

Although the ultimate trade-off analysis tool has not been completely developed, subsets of this capability exist today. They can be found at DOD simulator training facilities at Fort Rucker, Fort Knox, and Williams AFB; at the Army's Aeroflightdynamics Directorate at NASA/Ames; and at major DOD contractor facilities, such as Boeing, General Dynamics, and Sikorsky. Most of these interactive simulators are already electronically linked via the DOD Distributed Interactive Simulation network and additional contractors with their virtual prototypes are expected to join this "electronic battlefield" in the near future. During our visit to the Sikorsky facility, we were allowed to "fly" with the Sikorsky test pilot in the "Boeing Sikorsky RAH-66 Comanche Team's" virtual prototype of the Army's latest helicopter. One of the many current uses being made of this virtual prototype is the generation of data in support of trade studies.[25]

Major efforts are underway to improve the communications infrastructure in order to facilitate the completion of this futuristic electronic battlefield. The Clinton administration is committed to the rapid advancement and expansion of virtual prototyping technology and the budgets for the Advanced Research Projects Agency and the Defense Department efforts in this area now exceed one billion dol-

lars. The ARPA War Breaker project, for example, has recently been increased to more than $750 million.[26] Because it can provide the decision maker with an expanded evaluation capability, virtual prototypes will become essential to the system trade-off studies of the future. Color Plate 4, taken during Phase One (The Zealous Pursuit Exercise) of the ARPA War Breaker program, vividly illustrate the emerging "electronic battlefield" of the future.

COST ANALYSIS

According to guidance contained in DODI 5000.2, cost and operational effectiveness analyses (COEA) are prepared and considered at every acquisition Category I program milestone decision review starting with Milestone I, Concept Demonstration Approval. The COEA should aid decision makers in judging whether or not any of the proposed alternatives to the program offer sufficient military benefit to be worth the cost. There are several subanalyses that usually are utilized to develop the COEA. Analyses of mission needs, threat, measures of effectiveness, and costs are typically included in every COEA. Measures of effectiveness are used to gauge the military utility of specified outputs. The cost analysis, on the other hand, assesses the resource implications of associated inputs. Each cost estimate must be explicitly based on the program objectives, operational requirements and contract specifications for the system, including plans for such things as peacetime utilization rates and how the system will be maintained. Life cycle costs must be identified for each alternative being considered in the COEA and separate estimates of operations and maintenance costs must be made, particularly for manpower and personnel and training costs.[27]

Two separate cost estimates are prepared for Milestone I and all subsequent milestone reviews. One is prepared by the program office and the other by an organization not reporting through the acquisition chain. The Office of the Secretary of Defense Cost Analysis Improvement Group (CAIG) provides a report on the cost of acquisition Category ID programs to the USD(A&T) and for category IC to the DOD Component Acquisition Executive. The DOD Component responsible for the acquisition of a system must support the CAIG in the preparation of their report by providing cost, programmatic and technical information required to estimate the costs and appraise the cost risks associated with the system.[28] Usually, this information is provided in a work breakdown structure orientation and each cell of the cost estimate will usually have some type of cost rationale explaining the basis of estimate. Depending on the acquisition phase of the system, the cost analysis may be detailed and represent the work of a cost-estimating department that has spent a tremendous number of hours with design and manufacturing engineers trying to gain an appreciation for the magnitude of what and how it will be built. Estimating costs based on engineering sketches or even released drawings is a difficult task and inherent in the estimate that is produced is the estimator's assessment of risk to finalize the design and actually build the part, board or subassembly. The cost estimate associated with the final assembly and test of this new system is also significantly influenced by the cost estimator's assessment of the risk involved.

Translating the dimensional information on hundreds of drawings into a mental image of what the system will look like, how it will be built, how it will be tested, and then converting this information into a cost estimate is a significant challenge. This task, especially the risk evaluation, would be much easier and more accurate if the individuals involved in the cost-estimating process could somehow see and touch the product they are being asked to design and build. Instead of trying to

mentally visualize and cost a complex submarine command center that may take more than 1,000 engineering drawings 2-D format to describe, wouldn't it be helpful for a cost estimator to *enter* the submarine command center with the design and manufacturing engineers and together "see" the product that must be costed? The risk assessment by the cost estimator would certainly be more accurate if the engineer exercised the moveable parts, opened the door, raised or lowered the periscope and checked for interferences, could see and reach the display controls from the operator seat without having to stand up; demonstrated there are no two structures on the vessel trying to occupy the same space at the same time; and confirmed that the same database used to create this virtual prototype would drive the numerically controlled machines on the manufacturing floor to build identical hardware.

In addition to assisting the contractor and program office cost estimators, virtual prototypes can be used to provide valuable cost-estimating information to the CAIG. Most important of all due to their digital nature, they could actually be brought to the milestone decision briefing and allow the decision makers to gain a firsthand impression of the system being evaluated.

RESEARCH AND DEVELOPMENT

Requirements Definition

As discussed earlier, DODD 5000.1 specifies the management framework within which military requirements are expressed initially in broad operational terms. Throughout this process there is ample opportunity to utilize virtual prototyping and simulation to enhance the effectiveness of requirements refinement.

Recognition exists today at the highest levels within DOD that Advanced Distributed Simulation and, thus, virtual prototyping can "markedly improve the requirements definition and refinement; research, development, and acquisition" process.[29] Distributed interactive simulation and virtual prototyping can create a synthetic environment where operational and technical innovation can flourish. One can examine what current systems are doing and ask how those systems can be better employed, used in new and different ways, improved upon or replaced with other capabilities. General William E. DePuy, USA (Ret.), believed research and development is a circular process:

> *The relationship between the research community, the developers and the users, is clearly circular. That is, the relationship is interactive and continuously so....Research is not conducted without an awareness of potential applications. Development of those applications is not undertaken in an employment vacuum. Concepts of employment are a synthesis of tactical experience and new technical capabilities.*[30]

While the defense acquisition process as described in DODD 5000.1 appears to be a linear activity from the sequence of the milestone decision points, the activities prior to Milestone 0 and within each phase are circular in nature — especially in the early portion during requirements definition and concept studies. The goal of this circular process is to establish the military worth of new concepts and new hardware.

A powerful example of how virtual prototyping can be beneficial was conducted by General Paul F. Gorman, USA (Ret.), who led the presentation of DIS technology to the Senate Armed Services Committee on 21 May 1992. Included in the presentation was a virtual prototype of a Line of Sight Anti-Tank (LOSAT) weapon whose components have been partially developed and tested but for which there is no weapon system in DOD.

This virtual LOSAT was operated on an electronic battlefield consisting of an F-16 fighter aircraft, an AH-64 attack helicopter and an OH-58D observation helicopter and an M-1 tank — all manned simulators. The significance of this demonstration was:

— Virtual prototypes can be produced quickly and at a relatively low cost compared to physical prototypes.

— A great amount of realism can be incorporated in the simulation.

— Proposed weapon systems can be endowed with characteristics for which technological solutions are not immediately at hand and without the expense of achieving the technical solution.

— Virtual prototypes can be operated by the user in advance of committing funding and large development programs to produce an article for test and evaluation.

A second successful example of virtual prototyping can be seen in the experience of the M-1 tank upgrade program. In 1984, the Army initiated a physical prototype of an M-1 tank with upgraded fire control and loader functions. After 24 months and at a cost of $40 million, the prototype was not functional. Effort was shifted from a physical prototype to a virtual prototype using a modified aircraft dome in 1986. Within six months and at a cost of $1 million, the test objectives were achieved. Virtual prototyping has substantial potential to improve and shorten the time from requirements definition to physical prototyping.

Virtual prototyping allows investigating the feasibility and conducting risk assessments on potential weapon systems. Virtual prototypes can increase the confidence of a design prior to constructing the physical prototype, thus decreasing cycle time and reducing costly errors. As confidence increases, one can consider skipping steps in the acquisition process since the basis of skipping steps is confidence.

Engineering Design Support

As a system proceeds from the concept stage into engineering development, modeling, simulation and virtual prototypes play an important role. Numerous engineering design issues, including mechanical stress, heat transfer, radar response and flight dynamics, to name a few, are best solved using virtual prototypes. Using virtual prototypes is not a substitute for physical testing, but it can speed up the testing process by ensuring the first physical items built are highly accurate. Many cycles of design alternatives can be "tested" quickly before committing to building a physical prototype. This technique avoids false starts which waste time.

Virtual prototypes allow design engineers to visualize the end product of the design process. Visualization is an effective stimulus for the creative thought process due to the large amount of information which is absorbed at one time. The ability to visualize a product also contributes favorably to the concurrent engineering process. Three-dimensional models can be viewed and understood by designers from all disciplines more easily than 2-D drawings that are often rendered for a specific discipline.

TESTING AND EVALUATION

Early Operational Assessment

According to guidance provided in DODI 5000.2, multiple design approaches and parallel technologies must be pursued, when warranted, in Phase I, Demonstration and Validation, of an acquisition. Requirements for this phase include an evaluation of supportability and manufacturing process design. Prototyping, testing and early

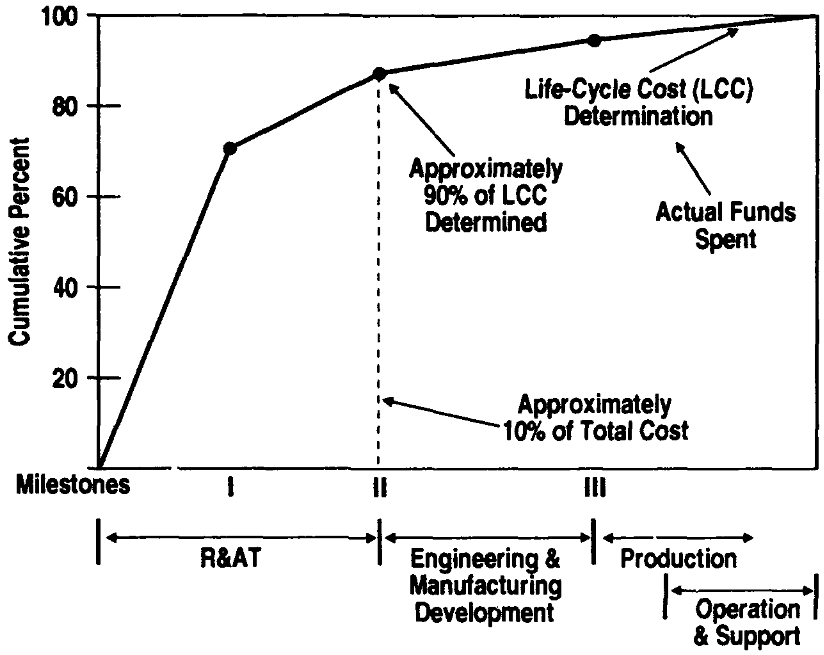


Figure 39. **Cost Impact of Program Decisions**

operational assessment of critical systems, subsystems and components are to be emphasized. Cost drivers and alternatives must be identified and analyzed, and each design approach must be further analyzed as a function of risk and the expected increase in operational capability.[31]

It is extremely important these evaluations are as accurate as possible because historical data, shown in Figure 39, indicates that more than 80 percent of a total system cost is determined by decisions made prior to the end of the Demonstration and Validation Phase.

The purpose of prototyping, testing and early operational assessment is to identify and reduce risk, and assess the most promising design approach to determine how the system will operate in the intended operational environment. This assessment must address the performance impacts on the system associated with the human operator, as well as the ability of the design to operate under different environmental conditions.[32]

Because the cost of full-scale prototyping for today's major weapons systems is so large, many contractors are developing a lower cost alternative to accomplish these critical Phase I evaluations. High-fidelity simulation now permits designers to create a virtual prototype that can be used for the majority of these evaluations, including operator and environmental assessments. Figure 40, provided during our visit to the Boeing Sikorsky RAH-66 Comanche Team, highlights the many uses of their virtual prototype, referred to as the Comanche Piloted Simulation.

Virtual prototypes are being utilized for early operational assessments by commercial as

COMANCHE PILOTED SIMULATION

SIMULATION

We use it for:

- **Iterating on the design of the crewstation cockpit**
- **Evaluating prototype designs in a realistic environment**
- **Developing flight control laws and assessing aircraft handling qualities with respect to specification requirements**
- **Generating data in support of trade studies**
- **Prototyping design concepts and filtering them before they are committed to an aircraft design, prototype or production**
- **Defining detail elements of the pilot vehicle interface specifications**
- **Defining/Identifying crew workload and confirming predictions from other methodologies.**

Figure 40. **Virtual Prototype Utilization on Comanche**

well as military contractors. Boeing Aircraft is using their virtual prototype of the Boeing 777 to accomplish numerous operational assessments prior to actual production and assembly. Boeing has such a high level of confidence in the fidelity of their virtual prototype that they are not going to build a physical mockup or flyable prototype.[33] Additional examples of companies using virtual prototypes for early operational assessment can be found in Chapter 5.

DEVELOPMENTAL AND OPERATIONAL TEST DESIGN

Policies and procedures establishing the basis for conducting test and evaluation activities in support of the DOD acquisition process are set forth in Part 8 of DODI 5000.2. The policy states that test and evaluation programs are structured to:

—Provide essential information for assessment of acquisition risk and for decision making

—Verify attainment of technical performance specifications and objectives

—Verify that systems are operationally effective and suitable for intended use

—Provide essential information in support of decision making.

Test objectives for each phase shall be designed to demonstrate system performance appropriate to each phase and milestone. Test planning begins in Phase 0, Concept Exploration and Definition, and continues throughout each subsequent phase. Developmental and operational testers are involved to ensure

the test program for the most promising alternative can support the acquisition strategy. Test planning, at a minimum, must address all system components critical to the achievement and demonstration of contract technical performance specifications and minimum acceptable operational performance requirements specified in the Operational Requirements Document. The Test and Evaluation Master Plan (TEMP) should focus on the overall structure, major elements, and objectives of the test program that is consistent with the acquisition strategy. Live fire testing and evaluation must be conducted on Category I and II programs for a vehicle, weapons platform or conventional weapon system designed to provide some degree of protection to the user in combat. It also must be conducted for a major munition or missile. Testing shall be planned and conducted to take advantage of the existing investment in DOD ranges, facilities and other resources, wherever possible.[34]

The specific content and format of the TEMP are detailed in Part 7 of DOD 5000.2-M, "Defense Acquisition Management Documentation and Reports," February 1991. The TEMP documents the overall structure and objectives of the test and evaluation program. It provides a framework within which to generate detailed test and evaluation plans and it documents schedule and resource implications associated with the test and evaluation program.

Now comes the hard part! What specific test should be required, and how should the test be structured to verify adequate performance against a given criteria? How many different scenarios and data collection runs are required to adequately demonstrate an acceptable product? What is the impact of the human operator on the performance of the system? Are all the system's critical operational displays within the operator's primary field of view? What is the impact of full sunlight through the canopy on the pilot's ability to read the mission critical instruments or the effect of night vision goggles on the pilot or crew member? If the budget only allows some finite level of testing, how is maximum return for each test dollar realized? Determining *what* and *how* to test thus is not an insignificant task; it is potentially as difficult as *conducting* the test.

Today's computer technology, if properly applied, is capable of providing the developmental and operational tester with a way to conduct meaningful evaluations to aid in designing the tests to be performed during each acquisition phase. A virtual prototype, developed as a scientific visualization in the Concept Exploration and Development phase and continuously enhanced throughout the development process, can provide the test community with the ability to optimize the number of tests to be conducted as well as reduce the time required to collect the required data. Because the virtual prototype exists in a digital world, the tester has the opportunity to conduct numerous iterations of the same test scenario and thus isolate the critical test issues that have the highest impact on the validation and verification of the system's critical developmental and operational parameters.

The visualization and fidelity of some virtual prototypes have now reached the stage where the engineers and testers are able to obtain more useful data from the virtual prototype than from an operational physical mockup. By using a virtual prototype, the tester can electronically change the environment, threat and platform speed and measure the resultant impact on system performance. This information can then be used to optimize the required test designs. It would be almost impossible to achieve or afford this level of test flexibility in the real world. Figure 41 contains the Boeing Sikorsky estimate of the developmental test

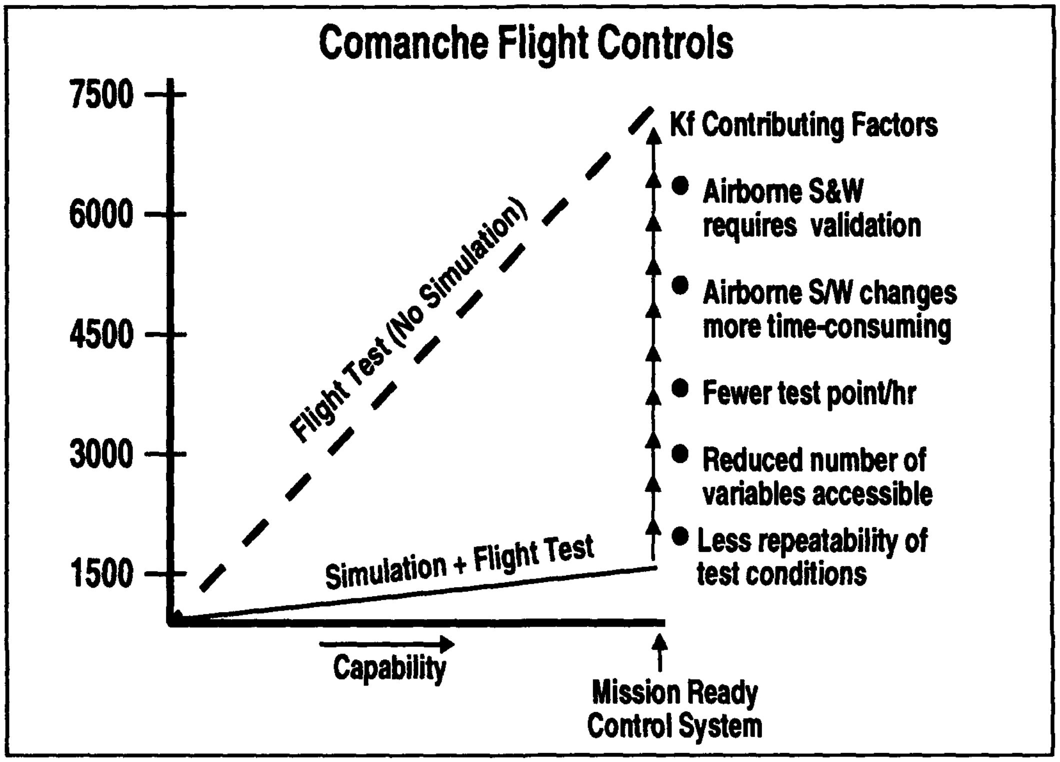


Figure 41. **Comanche Virtual Prototype Developmental Cost Savings**

hours that can be saved in the Comanche flight controls area through use of their simulation capability.

Sikorsky engineers believe the more the complexity and capability of the developmental system is increased prior to production, the more significant is the expected cost benefit from the use of simulation. This relationship is extremely important and should be one the government stresses in its consideration and negotiation of resource allocations for future capability enhancements. Total system savings resulting from the use of the Comanche simulation (virtual prototype) are estimated to be more than $600 million. See Chapter 5 for a more detailed discussion of simulation on the Comanche program.

Is there a way to accomplish all or a portion of the developmental and operational test without having to actually fly the aircraft, drive the tank, or fire the missile? Building operational prototypes to accomplish each of these tests can be extremely expensive and time-consuming. This situation may be further exacerbated if the type of test called for requires multiple evaluations under different environmental conditions. If each missile prototype costs several million dollars to build, or a billion dollars in the case of the RAH-66 helicopter or the F-22 aircraft, minimizing the number of physical prototypes required to accomplish the internally or externally required developmental and operational evaluations would be extremely cost beneficial. Substituting a virtual prototype for a physical proto-

type in all or some portion of the tests involving destructive testing and fatigue analysis would allow the tester to "dry run" the test scenario to optimize it for the real prototype, determine practical test limitations, and in many cases actually conduct additional tests that may not be affordable if the virtual prototype did not exist.

A more productive and affordable test alternative might be to use a virtual prototype to evaluate the system without having to build any physical prototypes. Based on our research visits to commercial as well as military contractors, we believe the current virtual prototyping capabilities have eliminated the test community's need for most physical prototypes, especially in the DOD acquisition phases prior to Engineering and Manufacturing Development. In commercial product development such as automobiles and aircraft, virtual prototyping has the potential to eliminate at least one iteration of the development cycle while still providing the necessary test data to support developmental and operational assessments such as operator visibility, ease of use, vibration, crash tests and customer feedback. The Boeing discussion in Chapter 5 provides an additional example of how virtual prototypes are being utilized by innovative contractors with state-of-the-art capabilities.

EXCURSION AND SENSITIVITY ANALYSES

Evaluating different approaches to a particular objective has always been one of the main functions of the analytical community. Can the problem be solved by a commercial aircraft carrying an observer with a Brownie camera; will a commercial aircraft with a high resolution CCD camera and a powerful workstation be required; or are special military aircraft and expensive sensors necessary? Include in this analyses an evaluation of a standoff platform with long-range sensors as well as a low-flying aircraft with shorter-range sensors requiring overflight authorization. Also consider an alternative that uses a high-flying platform requiring overflight. An evaluation of all these different excursions may be directed before a program approval is given. Even within an approved program the desire or requirement to evaluate different alternatives is constant. The user, OSD and Congress want to know what would happen if a different radar was installed in the aircraft, the existing individual displays were replaced by a multifunction display, or one of four workstations on the platform is eliminated? Currently, evaluations for the types of excursions mentioned would be based on a paper study that takes data from available technical data sheets; combines it with the expected environmental conditions, desired photo characteristics resolution and stabilization requirements associated with short- or long-range optics; and then attempts to piece together a composite set of information representing the performance that could potentially be obtained from each aircraft excursion evaluated. Unless one of the excursions was based on an existing system, the paper analysis will not provide an accurate total system performance because the analysis has no way to evaluate all the potential interactions of the various components, environment and the human operator. How stable the aircraft actually flies in a given environment and whether the vibration imparted to the camera mount causes unacceptable distortions all go together to create uncertainty in how well the individual pieces might function together as a hardware system. Couple this with the hard-to-characterize performance impact of a human operator on a given set of equipment, and the total system performance evaluation can be little more than an educated guess.

In sensitivity analysis, the analyst will vary one input in the equation, model, forecast, etc., and then analyze the impact.[35] Compar-

ing the delta change in the end result to the delta change in the input used to cause the change for every variable in the model will yield sensitivity data the analyst can use to identify areas where the most benefit can be gained for the smallest incremental increase. Sensitivity analyses in DOD applications are designed to show how military utility is affected by changes in system capability. For example, increasing a system characteristic such as size or weight by a certain amount may impact the system's performance which, in turn, may affect military utility or effectiveness. The analysis will show where we are on the curve and whether the desired performance is stretching the system to where increases in performance add little benefit.

Sensitivity analysis illuminates the importance of incorporating certain features in a system. Is adding wing surface, changing wing shape, or altering some other design parameter the best way to increase aircraft lift? In theory, sensitivity analysis should be relatively straightforward since only one input is varied in the equations being used to define the condition. Each part of the equation can be subsequently evaluated in the same manner to determine which factor has the greatest impact on the result. This scenario, however, becomes much more complicated when real-world measurements are required to confirm the equation accuracy or when the situation or condition to be analyzed cannot be completely and accurately represented by mathematical equations. Unless multiple versions of the excursion can be operated simultaneously, repeatability of the evaluation for sensitivity of a specific variable may be difficult to obtain. The humidity, amount of sunlight or temperature may have changed before another evaluation can be conducted.

Sensitivity analysis associated with an underdeveloped system can be even more challenging. Trying to characterize the system in a set of equations that will reflect system performance accurately may be beyond the capability of today's analytical systems. If a virtual prototype existed as the basis for each excursion, evaluation could be accomplished meaningfully and convincingly. Each excursion could be exercised against a specific target set on the electronic battlefield and the resultant data could be analyzed to determine which hardware configuration produced the most beneficial performance. Because the environment used for the evaluation of excursions is represented in a digital format, it lends itself to unbiased and accurate assessments of each excursion. The electronic battlefield is even more useful to sensitivity analysis because the same scenario can be run repeatedly with the assurance that variables such as weather, time of day, platform speed, or turbulence will be the same unless intentionally changed by the analyst. Virtual prototypes operating in an electronic battlefield will become a powerful sensitivity analysis tool the analyst can use to optimize system performance, and this optimization can be accomplished before any hardware manufacture begins. During our visit to Boeing, for example, they demonstrated how they successfully used their virtual prototype of the F-22 in sensitivity analyses in the design process to reduce the radar signature.

PRODUCTION AND LOGISTICS

During 1992, the Defense Science Board (DSB) evaluated manufacturing processes and laid out the vision of M&S application in the engineering and manufacturing process. The term Integrated Product Process Development (IPPD) is used to describe all activities occurring from concept development to field support. The primary objective of the IPPD initiative is to optimize system design and manufacturing processes. Figure 42 shows the future vision of how the battlefield is tied to the factory floor by the IPPD process. With the necessary tools and communication links,

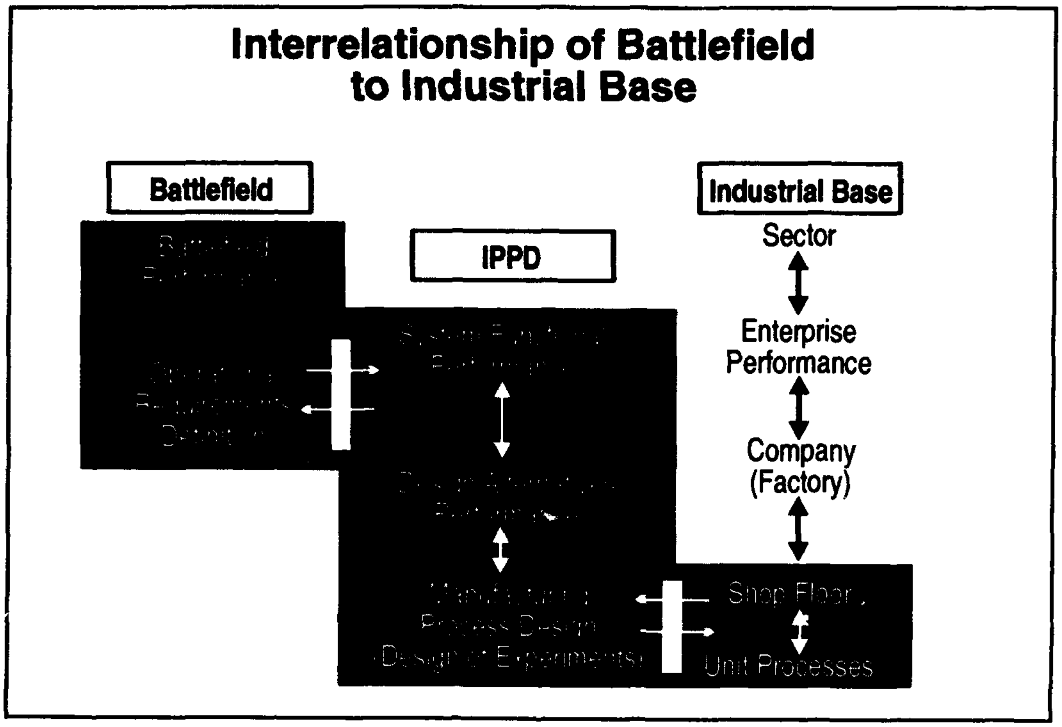


Figure 42. **IPPD (Source: Defense Science Board)**

the figure emphasizes the "feed-back/feed-forward" capabilities among the various environments available to enhance decision making. Work has already been done by DOD to transform this vision into reality. The ARPA is encouraging the development of affordable tools and technologies to support IPPD. Additionally, being developed are communication standards and formats for a broad range of M&S tools that must function harmoniously to achieve the vision.

The DSB divides production and logistics into four parts. Discussed below is a summary of DSB comments on specific M&S tools and technologies for manufacturing. Virtual prototyping offers great potential for achieving affordable weapons systems tailored to the specific needs of warfighters.

The Vision

The DSB vision of IPPD covers the decade of the 1990s and reflects the capabilities they believe are achievable during this period to support versatile and cost-effective engineering and manufacturing processes. Expanded applications of M&S will accelerate the full implementation of IPPD. The DSB expects M&S will progress in different stages for the various sectors of the industrial base during the next three to five years. The ARPA has targeted funds for the critical areas of this process. Various tools, some existing while others need to be developed, will substantially affect IPPD implementation. The DSB is confident weapon system concepts will be developed, tested and evaluated using simulation with minimum essential prototype fabrication and physical test and evaluation in the future. Dis-

tributed interactive battlefield simulation will play an important role in IPPD implementation. The SIMNET will allow warfighters to assess the value of new weapon systems and technologies in the combined-force battlefield environment. This distributed interactive simulation capability will be complemented by real-time hardware and warfighter-in-the-loop engineering simulations to bridge the gap between the current engineering design environment and the new synthetic battlefield environment.

The DSB sees the engineering M&S capabilities that will be developed and implemented during the decade as a critical element in the IPPD process. Improved fundamental understanding of the manufacturing process gained from modeling research will enhance the ability to optimize manufacturing processes for specific applications. Trade-off analysis of factory capability can provide an accurate assessment of production costs to enter into full-scale development of candidate weapon systems. Finally, the engineering M&S tools developed during the decade will permit maintainability, reliability and related supportability specialists to participate in the weapon system design process at the very beginning, permitting supportability to be designed into the product.

The ARPA and the U.S. Army have already initiated projects in warfighter-in-the-loop engineering simulations to emulate the costly and time-consuming conventional process of design, fabrication and testing. Warfighter-in-the-loop engineering simulations are intended to support engineering performance simulation at a design level of detail and assist the quantification and measurement of human response. The goal is to create the level of realism required for the weapon system simulations to function effectively in the hands of a broad cross section of warfighters. Along with carefully planned hardware-based experiments for simulation, validation and parameter determination, a fundamental understanding of critical engineering trade-offs using virtual prototypes is anticipated.

Current Needs

The DOD Manufacturing Technology (ManTech) Program sponsors research aimed at developing new and innovative manufacturing technology and advanced manufacturing processes for more economical, timely and reliable production of defense products. A task force was created in 1991 to develop a strategic plan for allocating ManTech investments. The plan would be more responsive to shifting economic priorities and advancing technologies. The task force discussed the:

—Need for DOD to continue providing increased flexibility and enhanced capabilities in the face of reduced funding

—Need to ensure next generation weapons systems would be developed in a timely, cost-effective manner

—Identification of which manufacturing technologies should be optimized to yield the highest return for DOD investment.

Within these guidelines the task force also sought to identify those manufacturing costs that are expected to consume a major share of defense procurement expenditures over the coming decade. They want to identify manufacturing technologies that are obstacles to effective production.

The analysis suggested significant gains could be achieved by expanding efforts to include soft manufacturing support costs such as production management and manufacturing engineering. For example, a breakdown of electronic purchased parts resulted in identifying fabrication, assembly and inspection as the dominant cost drivers among unit proc-

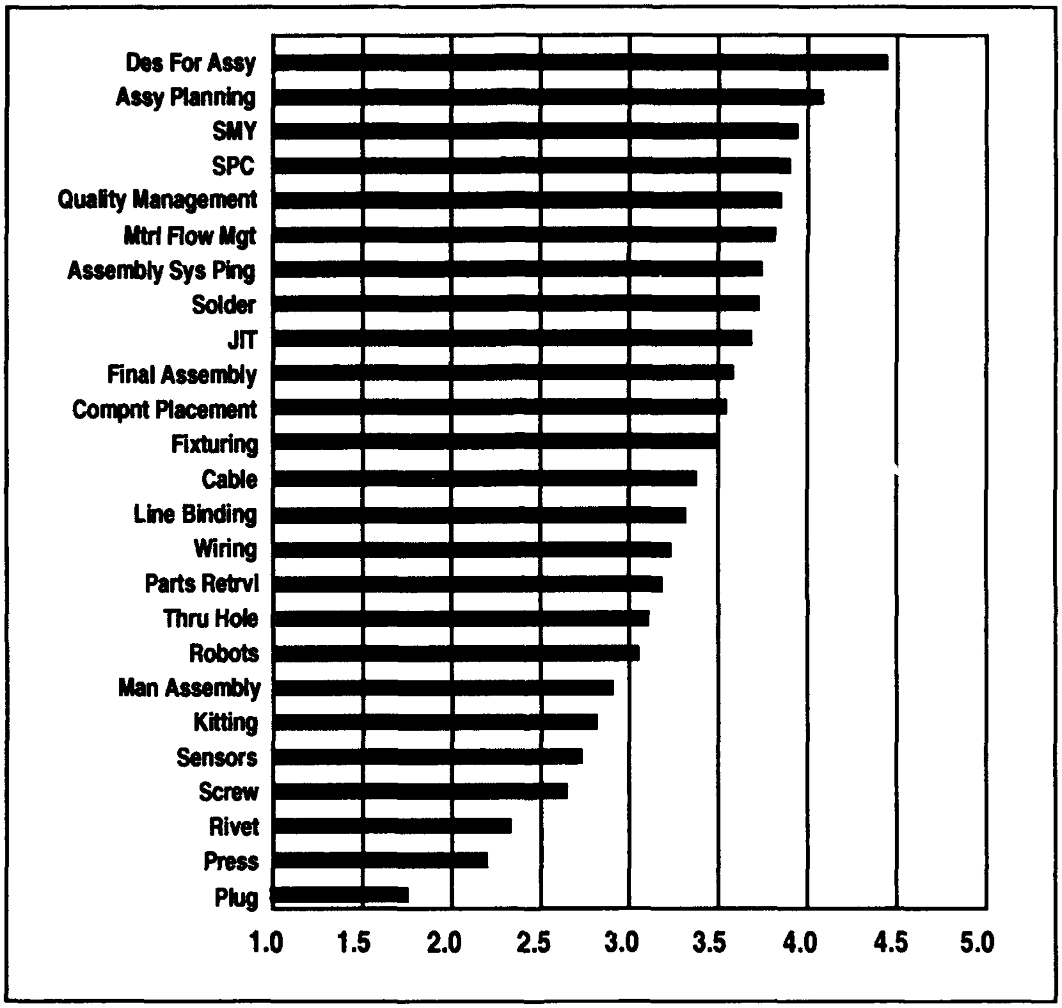


Figure 43. **Priority Scores: the Overall Survey**

esses required to manufacture these parts and subassemblies. The major recommendation of the task force was that more attention needed to be focused on identifying technical developments in those areas.

The study consisted primarily of intensive on-site interviews to collect information on the costs of assembly processes, assembly support and information systems along with data on technological opportunities and inhibitors. Based on this data, the study developed the data contained at Figure 43 which provides a quantitative assessment considering the importance, need and cost. The activities offering the greatest opportunities for payback were design for assembly (DFA) and assembly planning. Other assembly-related functions such as statistical process control, quality management, material flow manage-

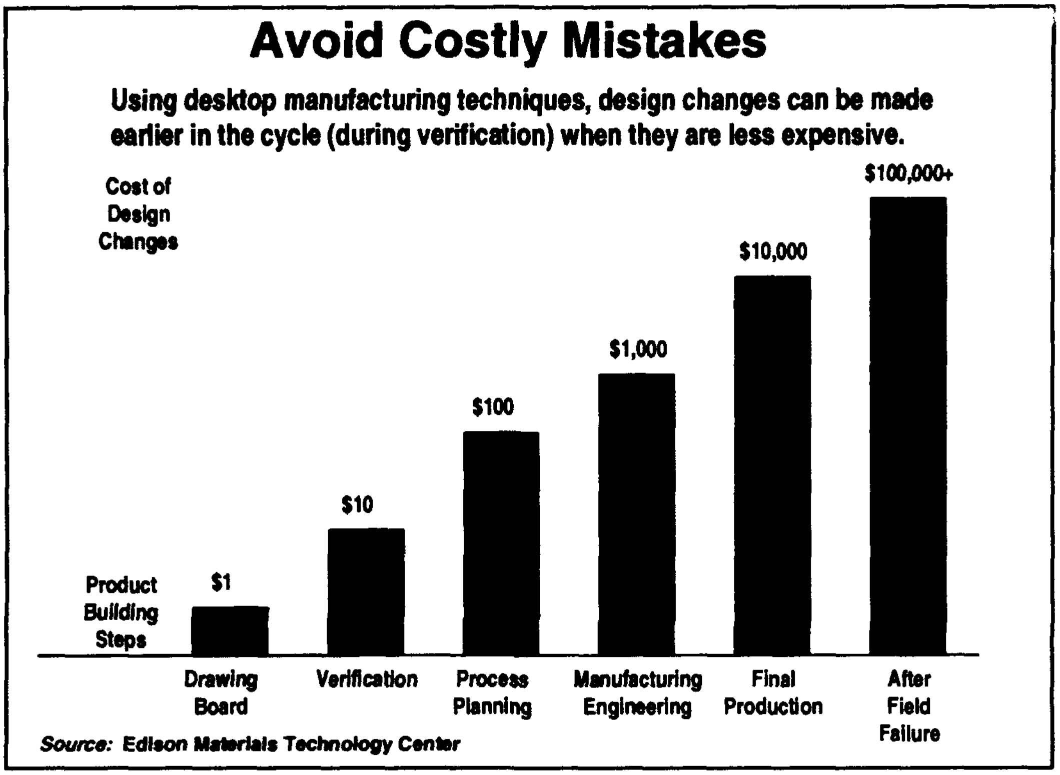


Figure 44. **Costs of Design Changes**

ment, and assembly systems planning are also important. The constant thread running through these areas is the need to develop systems to facilitate the coordination of design, assembly and quality functions in order to deliver manufactured products on time, within budget, and to acceptable performance measures. This backdrop emphasizes the importance of design in the manufacturing process.[36] The principal initiatives underway to address these problems are concurrent engineering and flexible automation.

Concurrent Engineering and Production

The objective of concurrent engineering is to accelerate all phases of product development by starting them as soon as possible and running them concurrently. Using computer models made available to many functional groups working in parallel early in the design process, concurrent engineering allows design changes before producing tooling or products thereby merging design, production and reliability considerations. The data in Figure 44, courtesy of the Edison Materials Technology Center, a materials and processing consortium based in Dayton, Ohio, underscores the savings that can be derived by making design changes early.[37] In addition, designs are intended to produce items that can be economically assembled with existing capabilities. The impact can be significant because "over 70% of product cost is committed at the design stage," according to respondents to the ManTech survey.[38] The key message of the study, particularly for DOD contractors,

was that regardless of past or present successes, investments in DFA activities have not been sufficient to realize the full benefits of this technology. As noted in Chapter 5, companies like Boeing and Kohler that have harnessed this technology are achieving significant competitive advantage.

The impact of designing the product for assembly not only reduces the number of parts but also simplifies all the related support functions of materials management, inventory control, and even accounting and purchasing procedures. Product design for automated assembly often results in a design that makes manual assembly straightforward with the predominant role of the operator shifting to a monitoring and quality management role. The design of tools for ease of assembly brings into play the role of ergonomics and its basic impact is the creation of a safer, more reliable work environment. Design for product supportability forces consideration of the life-cycle aspects of manufacturing including issues such as maintainability and reliability. Finally, design of the process for ease of assembly forces the integration of product and process personnel nurturing concurrent engineering. Activities that strive to eliminate, reduce or at least incorporate production constraints within the design process are destined to significantly impact the assembly cost and manufacturing in general.

The DARPA Initiative in Concurrent Engineering (DICE) is addressing many concurrent engineering obstacles. One of the principal challenges is the difficulty of enabling designers to work in parallel. Typically, participants in military time-critical design processes cross many disciplines, including users, designers, engineers and frequently geographically-dispersed manufacurers. The ARPA Collaborative Environment for Concurrent Engineering Design (CECED) encompasses new methods to facilitate communication between these participants. The goal of this program is to create a collaborative environment conducive for concurrent engineering. Figure 45 shows how this environment would be used.[39]

Concurrent engineering offers a number of significant benefits over current practices. See Figure 46. It promotes participation on an equal footing of all personnel involved in the product. Operating in a collaborative environment, players communicate using familiar tools and address concerns while the opportunity still exists to make changes. It aids program management and administration by forcing a dialogue among all affected parties and permits a comprehensive assessment of the total product. The likelihood parts won't fit or interferences occur is greatly diminished in a collaborative environment. It allows the exploitation of the information and technology explosion that is expected to continue in the 1990s.[40]

Concurrent Engineering and Reliability

Concurrent engineering benefits will extend throughout the product life cycle, as the designed-in reliability, maintainability, producibility and environmental considerations will result in reduced maintenance, spares and disposal parts. Simulations over the life cycle of parts will provide accurate data that precludes the manufacture of a flawed design, precipitating failures months or years later.41 A corollary benefit is the ability to identify over-designed parts. It may not be necessary to design a component to last 20 years when the system need only last for several years.

The bottom line is that concurrent engineering when properly implemented will produce items which incorporate state-of-the-art technology to satisfy customer needs and manufacturing capabilities. It is being implemented successfully and is a prerequisite to being

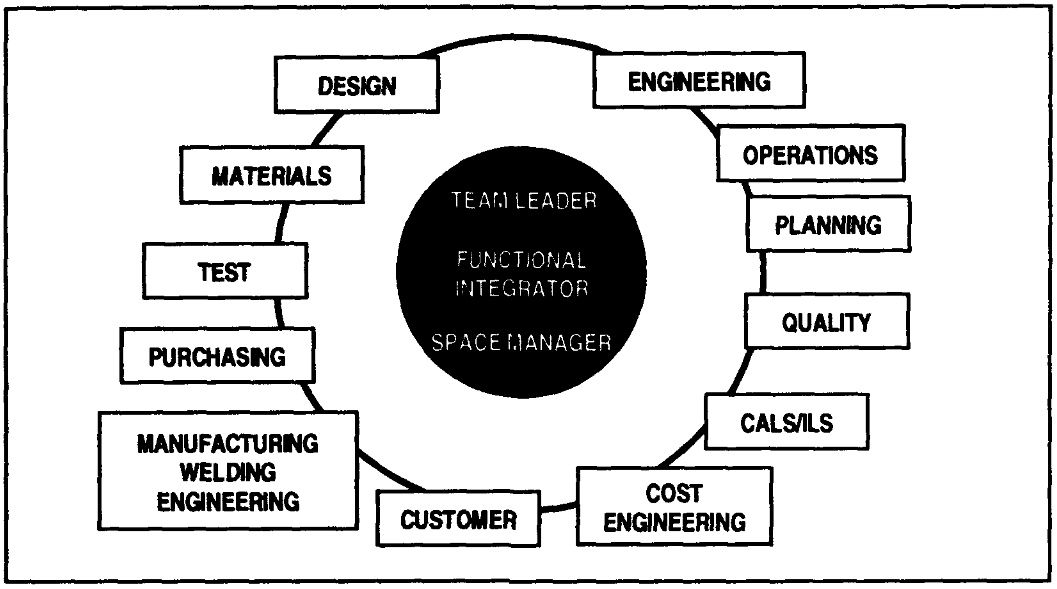


Figure 45. **Concurrent Engineering Environment (Source: ARPA)**

- **Promotes participation on an equal footing**
  - **Players use appropriate and familiar tools**
  - **Concerns are addessed while the opportunity for change still exits**
- **Aids program management and administration**
- **Permits comprehensive snapshot assessment of total vehicle concept for more informed decisions**
- **Allows exploitation of the "Information and Technology Explosion," which is guaranteed to happen**

Figure 46. **Benefits of Concurrent Engineering**

competitive in the future. Companies not embracing concurrent engineering during the 1990s will find it increasingly difficult, if not impossible, to compete.

Flexible Automation

The concept of a flexible manufacturing environment presents a number of opportunities. It can be used by a company for rapid prototyping, moving swiftly from a market-generated demand, through design and manufacturing analysis to the factory floor and ultimately to the consumer. It can be employed to enhance a company's capability to produce military and commercial products in the same facility. In a military context, it can be used to assess manufacturing surge capabilities. The underlying objective is to obtain highly-flexible and integrated manufacturing capability designed to respond quickly to a broad range of customer requirements. The concept of flexible automation embraces equipment and people. Flexibility is a critical building block of rapid prototyping and the concept of a virtual factory.

Rapid Prototyping

In the prototyping world, the operative word is speed: the faster you can design and optimize a conceptual model, the sooner you can produce and ship to market. Achieving a quick turnaround is not easy using conventional methods but with the help of rapid prototyping systems, also called desktop manufacturing, free-form manufacturing and 3-D printing systems, prototypes can be produced in a small fraction of the time and at minimum costs. Rapid prototyping lets companies transform computer-aided design (CAD) data directly into parts and models without ever going to the machine shop. Requiring an investment of $300,000 to $500,000, companies rapidly transform CAD drawings into parts and models. The benefit is a 30-95 percent reduction in development time and cost.[42] Figure 47 describes rapid prototyping methods, cost and capabilities for the various commercial processes.

How much does it cost a company to produce a benchmark part using today's rapid prototyping tools? Chrysler's Jeep and Truck Engineering group compared the costs of six rapid prototyping systems by producing the same benchmark part, a speedometer adaptor. The systems included the SLA-250 Stereolithography Apparatus, produced by 3-D Systems, Inc. discussed elsewhere in this report. Note that the total part costs ranged from $92.23 to $378.10. See Figure 48.[43] It should be noted that companies need not buy the equipment. Numerous service bureaus exist that will accept ".STL" files, the *de facto* standard format developed by 3-D Systems, and produce prototypes. The data at Figure 49 compares the total time required to make the part using the various systems including preprocessing and postprocessing time.[44]

In design engineering, the systems can provide quick conceptual models or actual prototypes for design reviews. They can enable engineers to execute form, fit and function tests; however, since they are not made out of the material with which they will be produced, they may not work like the actual part.

The parts can be used in manufacturing because the physical models show the complex geometry assisting producibility studies. Prototypes can also function as finished parts. They can be patterns for investment castings and can make urethane, rubber or epoxy molds to cast parts of varying materials. Some manufacturers say their parts can play an important role in marketing, especially to enhance client presentations. They can also be useful in purchasing by increasing the accuracy of bids received by including physical models as part of the bid package.

Reprinted from Rapid Prototyping MITIAC State-of-the-Art Report

Process Name	Method	Cost	Software	Max. Part Size	Hardware	Cycle Time	Materials	Accuracy	Comments
Stereo-Lithography	A	$105K-$420K	ABCDEFG	20"x20"x24"	AB	Variable	A	±0.002—±0.005"/"	AG
Solid Ground Curing	B	$550K	ADGHIJ	20"x14"x20"	C	100 layers/hr.	A	0.1% up to 0.02"	B
Selective Laser Sintering	C	$397K-427K	AB	12"dia.x15" high	D	0.4-2"/hr.	BDF	±0.015"	BE
Fused Deposition Modeling	D	$162K-$186K	ABC	12"x12"x12"	E	Variable	CEH	±0.005"	F
Laminated Object Manufacturing	E	$95K-$180K	A	32"x22"x20"	D	15-24 ips	GIJ	±0.010"	B
Hot Plot	E	$13K	E	16"x11"x12"	F	1.2 ips	K	±0.020"	BC
Design-Controlled Auto. Fabrication	B	$99.6K-$159.5K	ABE	22"x22"x24"	C	90/layers/hr	A	±0.001—±0.002"	
SOMOS/Soliform	A	Not Available	A	12"x12"x12"	B	Not Available	A	xy: 0.002"; z±0.006"	A
Solid Creation System	A	Not Available	ABE	40"x32"x20"	AB	Not Available	A	Not Available	
Computer-Oper. Laser Active Model	A	Not Available	A	12"x12"x12"	A	Not Available	A	Not Available	D
Stereos	A	Not Available	Not Available	16"x15"x24"	AB	Not Available	A	Not Available	G
Solid Object Ultra Violet Laser Plot	A	Not Available	A	34"x24"x20"	AB	Not Available	A	±0.002"	

KEY:

Method
- A- Point-by-point laser cure of liquid
- B- UV lamp irradiation of entire cross section in liquid
- C- Point-by-point laser sinter of powder
- D- Point-by point droplet deposition
- E- Sheets cut along periphery of cross section bonded together
- F- Electrodes energized in Electroset fluid solidifies entire part
- G- Thermal spray deposition
- H- Point-by-point metal deposition and welding
- I- Point-by-point binding of powder material

Software (accepted file formats)
- A- .STL file
- B- IGES
- C- NC codes
- D- VDA-FS
- E- HP/GL-2
- F- CAT scan
- G- NMRI/MRI
- H- SDRC-IDEAS 3D CAD files
- I- CAEDS 3D CAD files
- J- Pro-Engineer 3D CAD files

Hardware
- A- Helium-cadmium laser
- B- Argon-Ion laser
- C- Ultraviolet lamp
- D- Carbon dioxide laser
- E- Extruding head
- F- Electrode
- G- Piezoelectric ink-jet mechanism
- H- Electrode printer
- I- Thermal spray gun
- J- Welding machine
- K- Ink-jet printhead

Materials
- A- Photopolymer liquid
- B- Investment casting wax powder
- C- Investment casting wax wire
- D-Nylon powder
- E- Nylon wire
- F- Plastic powder
- G- Plastic sheets
- H- Machinable wax wire
- I- Paper sheets
- J- Composite sheets
- K- Polystyrene sheets
- L- Metal
- M- Ceramics
- N- Silicone rubber
- O- Wax
- P- Plastic
- Q- Epoxy
- R- Polymer

Comments
- A- Post curing required
- B- Integral support structure capabilities in system
- C- Labor intensive
- D- Part built from top down
- E- Potential for metal part production
- F- Quick material changeover
- G- Interchangeable vats
- H- Material properties are controllable

Figure 47. Commercial Prototyping Methods

Costs to Make Benchmark Part

VARIABLES	LOM 10/15/ Helisys	Sinterstation 2000/DTM	Solider 5600/ Cubital	SLA-250/ 3D Systems	SLA-500/ 3D Systems	3D Modeler/ Stratasys
Cost of equipment	$85,000	$397,000	$490,000	$210,000	$420,000	$182,000
Expected Life/Yrs.	11	11	11	11	11	11
Service Contract Expense	$17,000	$68,000	$49,000	$36,000	$85,000	$7,000
Part Expense*	$92.23	$175.49	$378.10	$112.59	$147.04	$154.07

*Includes depreciation, material, labor and overhead costs.

Source: Chrysler's Jeep and Truck Engineering

Figure 48. **Parts Cost**

Biomet Inc., Warsaw, Ind., designs and manufactures health-care products for orthopedic surgeons. Its success hinges on its ability to move a design from the idea stage to the operating room.

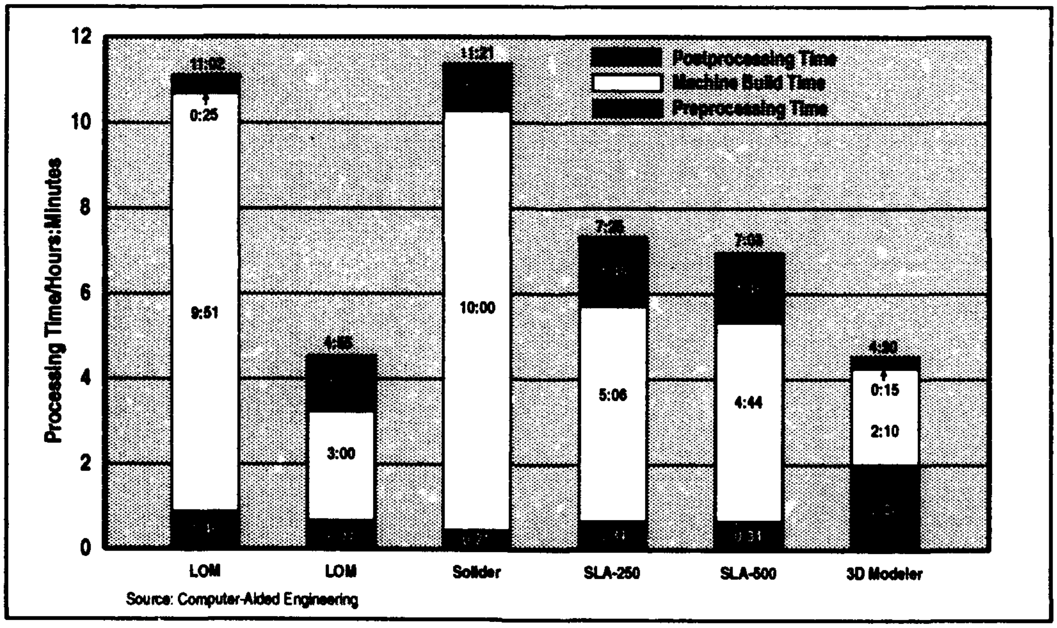


Figure 49. **Time Required to Fabricate Parts**

Critical success factors for succeeding at rapid evolutionary development are:

- **A committed and informed executive sponsor**
- **An operating sponsor–a champion**
- **Appropriate IS staff**
- **Appropriate technology**
- **Management of data**
- **A clear link to business objectives**
- **Management of organizational resistance**
- **Management of system evolution and spread.**

Figure 50. **Rapid Prototyping Organizational Challenges (Source: *Computerworld*)**

In 1990, Biomet's model shop spent 2,000 hours crafting models to support 11 new projects. Machinists used manual and numerically-controlled machines to construct each model from rough bar stock. Company officials could see the impact of rapid prototyping within other manufacturing industries and decided to invest in it.

> 'We looked at several rapid prototyping technologies,' says John Amber, Biomet's CAD/CAM manager, 'and decided Stratasys' Fused Deposition Modeling process best fit our needs.' The company brought Stratasys 3-D Modeler, setting it up right next to the CAD workstation in the office. Typically, models are built off CAD data in less than an hour. Accuracy is + or - 0.005 inch over a 12-inch cubed working envelope. The company estimates the 3-D Modeler will cut model-making time by 200% to 600%, allowing it to complete 50 projects scheduled for the year.

More prototypes faster is only one benefit: Biomet has used Stratasys' investment casting wax for direct output to the investment casting process. Small quantity production runs are now cast without expensive hand tooling.

> 'Moving from 11 new products in 1990 to 50 in 1991 would've been impossible without the kind of productivity boost this technology has delivered,' according to Farry England, Biomet vice president of manufacturing. 'Introducing the Stratasys system will allow us to meet aggressive production goals and to sustain our record growth.'[45]

Rapid prototyping techniques are being used increasingly by large U.S. manufacturers but, overall, analysts say this technology is still in its infancy. Major European and Japanese companies are working with the prototyping technology, tailoring it and expanding its uses. Analysts say most of the large Japanese electronics companies and automakers, for in-

- **Open Architectures**
- **Scalable Architectures**
- **Windows-based Interfaces**
- **Distributed Databases**
- **Fourth Generation Language**

Figure 51. **Rapid Prototyping Technological Challenges (Source:** ***Modern Office Technology*****)**

stance, now use some kind of rapid prototyping procedures.

Successful implementation of rapid prototyping requires organizational commitment and application of several key technologies. The key organizational factors for succeeding with rapid prototyping are listed in Figure 50. Note the importance of executive and operational sponsorship. A clear link must be established to business objectives, and management must be prepared to deal with organizational resistance. Additionally, an appropriate information systems staff is critical, along with technology and data management.[46] The key technological capabilities have been in place for some time; however, they are only now being applied in the development process as shown in Figure 51. Open architectures allow for the use of multiple vendor platforms; scalable architectures support multidimensional growth of hardware and software systems; window-based interfaces give users access to multiple applications simultaneously; distributed databases allow scaling without choking the system; and fourth generation languages allow the use of pseudo-English tools that can be manipulated by a system administrator rather than a programmer.[47] These challenges are being met today by companies who recognize the importance of speed and the key competitive advantages derived from bringing products to market first.

Virtual Factory

Modernization pressures and the astronomical costs of factory design, along with the cost of design errors, have made simulation an attractive planning tool. With current factory simulation packages, companies can model factories. These models differ significantly from paper models because they can simulate large periods of time unlike a snapshot provided by the paper method. It is a tool that can be used to evaluate the feasibility of adapting flexible assembly in a particular plant. It allows the user to explore a full range of manufacturing options — machinery, new or old; personnel, one or two shifts; and sourcing, build or buy. It can also be used to determine manufacturing capacity and the feasibility of converting from commercial to military products and vice versa.

Factory simulations are particularly important as companies grow or restructure. The simulations allow companies to describe activities and constraints and to rapidly evaluate various alternatives. For example, Schering Corporation performed a simulation

to determine if its pharmaceutical factories could meet forecasted demand. The company wanted to know if current facilities could handle an anticipated upswing in production. They needed to determine if new capacity would be needed, how much and whether it could be justified financially. The simulation revealed that even two shifts a day would fall short of anticipated production requirements.

Once understood, the company worked through four new factory scenarios before finding an optimal solution. This type of long-range evaluation capability has enormous potential for DOD as it proceeds with downsizing and restructuring. A virtual factory simulation capability can be used to assess the impact of plant closings, calculate surge capacity, and evaluate the feasibility of dual use applications.[48]

Significant Challenges

The DSB has identified six significant issues regarding the use of M&S in the engineering and manufacturing process.

1. Can M&S be used to shorten the time and reduce substantially the cost of conventional prototype fabrication and testing? The DSB concluded that the judicious use of appropriate M&S methods, concentrating on critical performance and manufacturing process issues, and taking advantage of available models of noncritical weapon performance and manufacturing capabilities can reduce significantly the time and cost of weapon system development.

2. What is capable of being modeled and simulated? Many aspects of weapon system performance are capable of being simulated with confidence, whereas some performance-related design trade-offs require real-time interactive warfighter- and hardware-in-the-loop methods not in existence. In addition, only selected manufacturing processes can be modeled now requiring that most simulations of manufacturing processes be carried out using physical experiments or empirical models based on experimental data.

3. What should be modeled and simulated? Critical weapon system performance and manufacturing process characteristics should receive high priority. The least cost and time-consuming M&S approach should be adopted to meet specific high priority needs in product and process design.

4. Is there an infrastructure to support M&S? This is a major challenge because the necessary infrastructure does not exist. Individual discipline-oriented simulation *tools exist, but most are embedded in specialized* organizations. Data communication standards and tools do not exist to exploit the broad range of tools required in weapon system and manufacturing process design.

5. Modeling and simulation can guide selective investment in the industrial base. However, models of the base do not exist, and it is uncertain if such a capability is feasible in the future.

6. Should M&S be used as a source-selection tool? Many sectors of the industrial base capable of M&S are capable of using M&S as a discriminator. The DSB suggested that the use of M&S in source selection be expanded.

The significant competitive advantages offered by concurrent engineering and rapid prototyping have compelled commercial firms to embrace the technologies and make organizational changes necessary to realize these benefits. The DOD should be able to

achieve these same benefits in its weapon systems acquisition if it maximizes the use of the technology in its acquisition process. Acquisition strategies, acquisition plans, requests for proposal, source-selection plans and MS criteria need to incorporate the concept of virtual prototyping as a fundamental element. That is, virtual prototyping should be the primary or central feature bridging all phases of the acquisition process.

ENDNOTES

1. DOD Directive 5000.1, p. 1.

2. *Ibid*, p. 1.

3. *Ibid*, p. 2.

4. DOD 5000.2-M, p. 1-1.

5. *Ibid*, p. 1-2.

6. DODD 5000.1, p. 1-2.

7. *Ibid*, p. 2-5.

8. *Ibid*, p. 1-2.

9. DODI 5000.2 p. 2-1.

10. DODD 5000.1, p. 1-3.

11. *Ibid*, p. 1-2.

12. DODI 5000.2, p. 4-B-3.

13. *Ibid*, 2-6.

14. *Ibid*, p. 2-5.

15. DODD 5000.1, p. 1- 4.

16. *Ibid*, p. 1-5.

17. *Ibid*, p. 1-5.

18. "A Review of Study Panel Recommendations for Defense Modeling and Simulation," Institute for Defense Analysis, June 1992.

19. "Defense Modeling and Simulation Initiative," Defense Modeling and Simulation Office, (1 May 1992).

20. Gossett. "CSRF/AVTB Network Demonstrations."

21. Lucas. "Designing Airplanes: Boeing's 777th Heaven," pp. 69-70.

22. Prichett. "Picturing Future Systems: TRW's Engineering Visualization Center," p. 5.

23. Rudwick. *Systems Analysis for Effective Planning: Principles and Cases*, pp. 341-373.

24. McDonald. "Distributed Interactive Simulation - Operational Concept (Draft)," p. 1.

25. Mr. Alansky of Sikorsky. "Comanche Simulation," briefing presented 3 March 1992.

26. Reilly, Lucy. "ARPA Budget Has Dual-Use Focus," *Computerworld*.

27. DODI 5000.2, pp. 4-E-1-6.

28. *Ibid*, pp. 10-A-1, 2.

29. 19 August 1992 Memorandum of Agreement between the Vice Chairman of the Joint Chiefs of Staff and the Director for Defense Research and Engineering on Ad-

vanced Distributed Simulation Applications, signed by Admiral David E. Jeremiah and Dr. Victor H. Reis.

30. 1985 postscript to "Changing an Army: An Oral History of General William E. DePuy, USA Retired," Center of Military History publication CMH 70-23.

31. DODI 5000.2, p. 3-13.

32. *Ibid.*

33. Lucas. "Designing Airplanes: Boeing's 777th Heaven."

34. DODI 5000.2, pp. 8-2-4.

35. Higgins. *Analysis for Financial Management*, p. 246.

36. DOD ManTech Task Force, "DOD's Manufacturing Technology (ManTech) Program," 18 December 1992 (Draft), pp. 24, 25.

37. "From art to part," *Computerworld*, p. 77.

38. DOD ManTech Task Force, "DOD's Manufacturing Technology (ManTech) Program," p. 24.

39. SRI International, "Environments to Enable Informal Collaborative Design Process," June 1992, pg. 1.

40. DARPA briefing, "Soldier-in-the-Loop Simulation for Improved Acquisition," 31 July 1992, p. 5.

41. DDR&E, "Defense Science and Technology Strategy," July 1992, p. II-66.

42. "From art to part," p. 77.

43. "Chrysler Compares Rapid Prototyping Systems," *Computer-Aided Engineering*, p. 84.

44. *Ibid*, p. 89.

45. "Cutting It in Rapid Prototyping," *Computer-Aided Engineering*, p. 32.

46. "Quick & dirty," *Computerworld*, p. 109.

47. "Rapid Prototyping As an Alternative to the Pilot," *Modern Office Technology*, p. 74.

48. "Working in a Virtual Factory," *Manufacturing Systems*, p. 19.

What, sir, would you make a ship sail against the wind and currents by lighting a bonfire under her deck? I pray ou excuse me. I have no time to listen to such nonsense.
— Napoleon to Robert Fulton

Chapter 5

EXAMPLES OF SYNTHETIC ENVIRONMENTS

One objective of this research project was to identify and assess the current applications of virtual prototyping by commercial companies, defense contractors and universities. This chapter highlights the significant applications we found during our research. The examples include applications on large defense and commercial systems at General Dynamics, Sikorsky and Boeing. It includes small, commercial, four-cycle engines developed and manufactured by Kohler, as well as research efforts at the Army's Night Vision and Electronics Sensors Directorate, the University of Washington, and the University of North Carolina. Our discussion documents the highlights of an on-site survey of the utility of virtual prototyping in a broad range of applications.

BOEING AIRCRAFT COMPANY

The Boeing 777 aircraft is being designed and built in a radically new fashion. See Figure 52. Using 2,200 workstations, eight IBM mainframes and IBM's CATIA CAD/CAM software, at a cost of roughly $100 million, the company is designing the 777 aircraft entirely on paper and plans to build it without a physical mock-up. The 777 aircraft has 85,000 components and more than 4 million parts. Boeing's goal is to make it the timeliest and most trouble-free program the company has ever undertaken.[1] Some refer to it as a paper-

Figure 52. **Boeing 777 Aircraft**

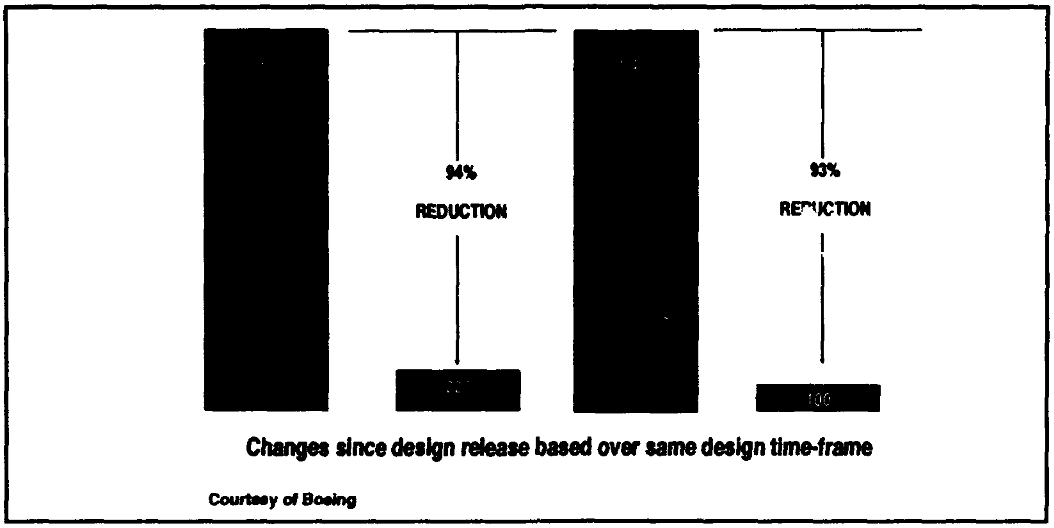


Figure 53. **Boeing 777 Design Quality**

less aircraft, but, "not so," according to Boeing senior officials who said that while they are relying on computer tools, customers will receive the same manuals and other aircraft documentation they now receive. Boeing adopted a digital design approach for three reasons:

1. Cost savings: The company's goal is to manufacture the 777 aircraft with the same number of manufacturing hours it took to produce the 767 aircraft even though the 777 has an empty weight 57 percent greater than the 767 aircraft.[2] The 777 aircraft, first scheduled for delivery in 1995, is designed to carry 375-400 passengers, with an initial range of 4,000 nautical miles while the 767, first delivered in the early 1980's, carries 220-300 passengers with a range of 6,000 nautical miles.

Boeing plans to achieve these cost savings by designing the aircraft so its parts fit together precisely the first time, thereby reducing the number of design changes required. According to Mr. Joe Ozimek, chief engineer of marketing management, the single biggest problem in industrial manufacturing is simply that parts don't fit. "We used to build an entire plane just to find out if the parts fit. What a waste of money." [3] The company checked the process itself by designing and part-checking one section of the aircraft and then building a mock-up of that. "The result was wonderful. Almost perfect!" This from a Boeing chief engineer who oversaw the mock-up. The only problem was three cable bundles were a bit short. Current data on the number of design changes also bears this out.[4] The company is experiencing a 93 percent reduction in design changes compared with design changes in previous aircraft. Early in the assembly process, this is a truly remarkable achievement. The data in Figure 53, provided by Boeing, illustrates this trend.

Another area of savings is in tooling costs. Previously, it was necessary to physically trace the drawings of the aircraft parts around which the tooling would be designed. Using digital design, plaster models have been replaced with digital data greatly improving

the precision and efficiency in building tools. Virtual prototyping has improved the accuracy of tool design by a factor of ten.[5]

2. Reduced manufacturing cycle times: Digital design and virtual prototyping can help reduce cycle time. Boeing wants to reduce production times by more than 50 percent to six months vs. 13 months.[6] Among the many challenges. of adapting a digital design approach was overcoming the inertia within the company. Digital design was a major cultural change. Drafting tables were literally replaced by thousands of computer workstations. From the beginning Boeing has planned to take more time to design the 777 aircraft than earlier planes. They adopted digital design to realize significant reductions in cycle time, but they also recognized that the transition would be difficult and time-consuming. They fully expect to realize dramatic savings on follow-on projects.

3. Customer satisfaction: Boeing has sought input from their customers continuously during the 777 design process and they have incorporated numerous design changes to meet customer needs. Representatives of United Aircraft, Inc., the kick-off customer for the 777 program, have played a critical role in the early design of the aircraft.

Changes brought about by customer recommendations included making a hydraulic accumulator smaller and lighter since the airline did not need the 12 hours of hydraulic pressure initially planned. The airlines informed Boeing they couldn't economically afford to have a plane idle for that long, so the system should not be overdesigned. In another example, trailing edge flaps were manufactured in two pieces so they would fit in the autoclave used by United. Boeing modified the push buttons used to pop open access panels for items such as auxiliary power units and air-conditioning packs were enlarged to allow a mechanic wearing gloves to activate them.[7]

Boeing also tailors an aircraft's features to meet specific customer requirements. Seat configurations, galley capabilities, engines, navigational equipment, fuel capacity and cargo-holding capabilities are items that usually vary by customer. No two planes are exactly the same. It is also common for airlines over time to modify their planes in response to different routes and market conditions. Customizing the 777 for customers will be easier in the future because Boeing will maintain the digital design data used to manufacture each aircraft. This digital information will be used in any redesign or customization efforts.

Boeing employed 238 design-build teams to design the 777. The teams included production personnel, supplier representatives, airline workers and design engineers. The process was intended to end the traditional isolation of disciplines and force the participants to work out solutions. Engineers creating the 777 hydraulic conduit didn't just assume it could be manufactured for $7,000; they asked the supplier's representative on the Boeing team.[8]

GENERAL DYNAMICS - ELECTRIC BOAT DIVISION (GD/EBD)

The GD/EBD in Groton, Conn., designs and builds the majority of the U.S. Navy's most sophisticated submarines. The magnitude of this task demands computer automation be applied not only where it is cost-effective in the short run, but where long-term advantages can be anticipated reasonably. The GD/EBD believes the greatest potential for cost reduction in the life-cycle cost of a system exists during the engineering design phase. Accordingly, it is implementing a Production

Automated Design Process (PADP) with the goal of reducing cycle time and cost, and improving product quality by integrating the engineering design process and manufacturing considerations early in the life cycle. Based on the latest digital design concepts, GD/EBD expects to reduce substantially the cost of submarine design and construction and to be able to integrate PADP with proven shipyard production control systems. Electric Boat will implement PADP in an evolutionary manner that involves a commitment from top management, extensive training and a continuous review and improvement process. The challenge is to maintain an acceptable balance between short-term additional costs and long-term cost savings.

Figure 54 shows the old, time-proven design process at GD/EBD — a manual design technology that results in a life-size physical mock-up of a submarine.[9] The physical mock-up serves many purposes, for example, physical fit of components, interference and clearance checking, visualization, production process visualization, and drawing confirmation. The proven physical mock-up is then translated into electronic format and stored in a drawing-oriented database. The database is used to generate conventional design drawings by discipline, such as electrical, structural and fluid. The database also allows limited computer graphics display of the design and the generation of single discipline construction drawings for the various sections of the submarine. Detailed production planning and the generation of multidisciplined product structure documents is, for the most part, a manual process which relies heavily on the physical mock-up for visualizing and understanding the complex product and manufacturing process.

The physical mock-up is the anchor for the design process. The confidence generated in the design engineers and managers by the physical mock-up is well deserved since this approach to building submarines has proved successful in the past. In fact, this confidence is so strong it might be described as an "impediment to change" if one proposes to eliminate the physical mock-up from the design process!

A physical mock-up for a submarine is expensive to build and maintain. It must be built with sufficient precision that measurements taken at the mock-up can be relied upon during construction of the final product. Finally, the value of the mock-up in allowing engineers to visualize the product cannot be dismissed lightly. Replacing the mock-up with a virtual prototype will require time and training before a cultural change in engineers and managers can be accomplished.

During our visit, GD/EBD explained how they are moving to a new design process where the anchor for the process will be a parts-based database rather than a drawing-oriented database derived from a physical mock-up. The new database will be structured with individual parts as the basic elements. Attached to each part in this database is all the information needed to use the part in a design — description, drawings, sources, substitutions and engineering characteristics, such as weight, electrical, thermal and strength, for example.

As parts are designed or selected from outside sources, they are entered into the database and become available for reuse, thus promoting standardization and the ability to distinguish between parts manufactured to stock and parts built to installation requirements. The design process results in building a database containing all the information about the parts in the submarine, how they are associated with each other, and how they will perform. The database contains reusable information from design through construc-

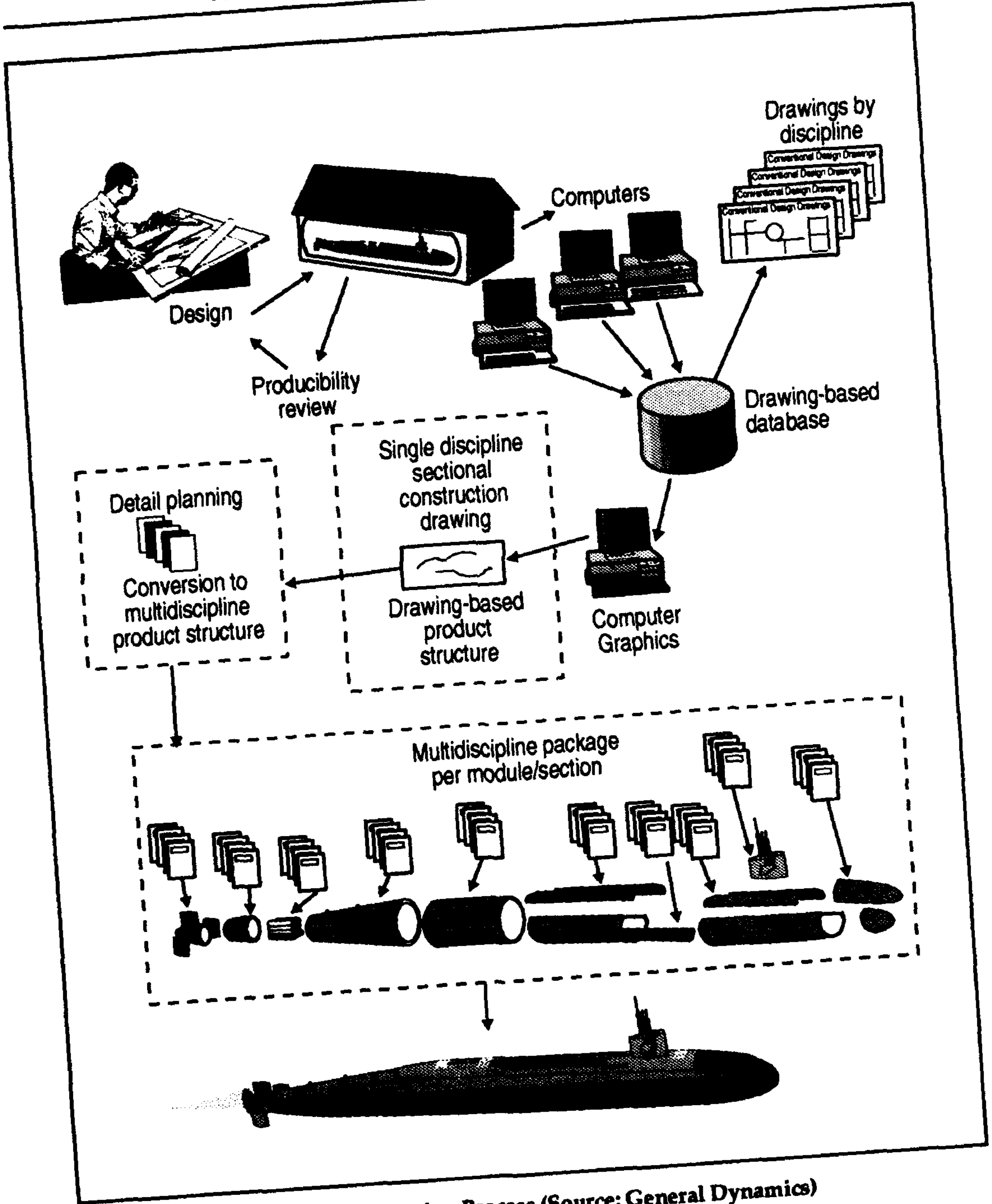


Figure 54. **Manual Design Process (Source: General Dynamics)**

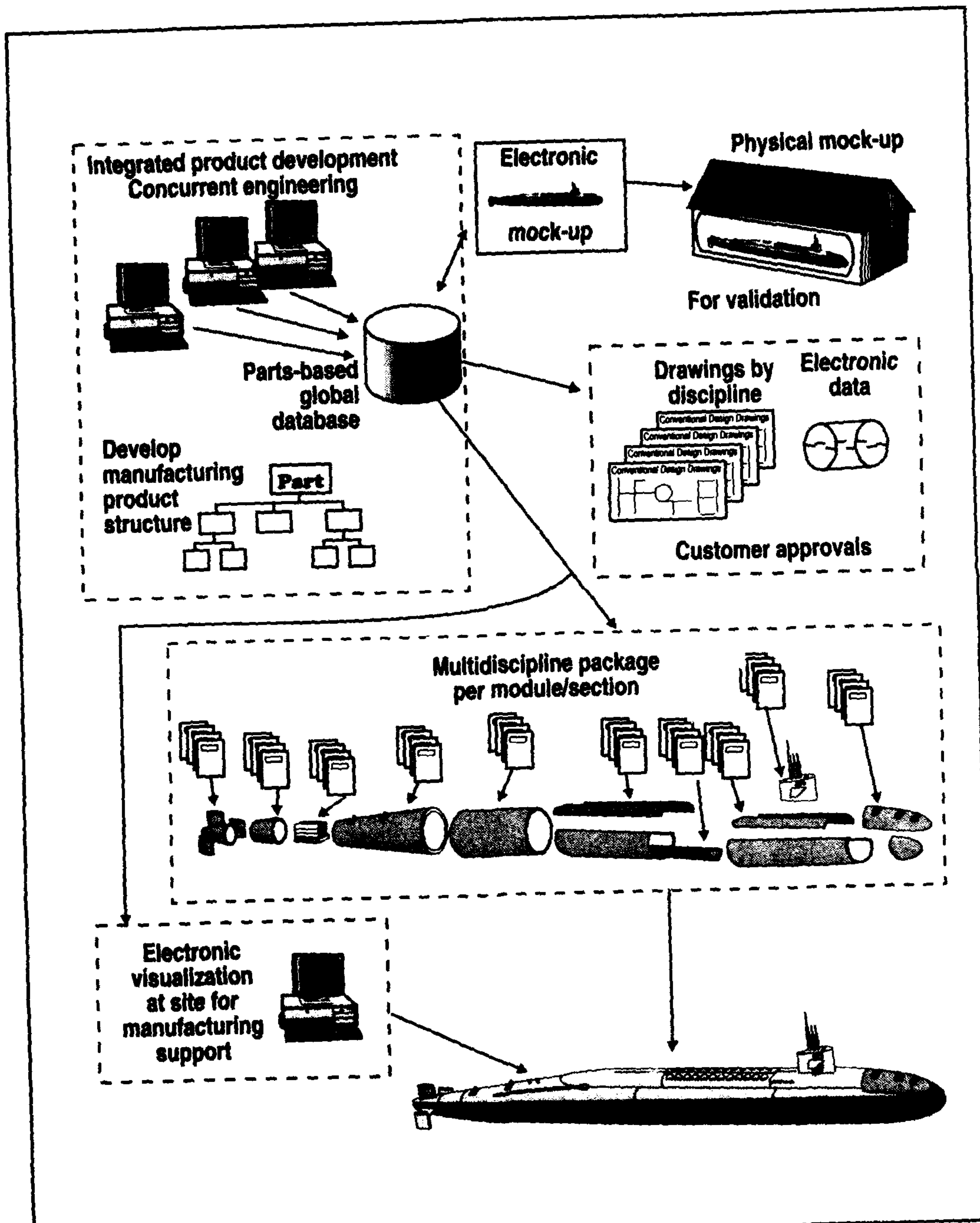


Figure 55. **Electronic Design Process (Source: General Dynamics).**

tion and supports an efficient and flexible mechanism for product changes.

Having a global database that contains all the design information and using an integrated multidisciplinary design team, concurrent engineering techniques will lead to a reduction in the number of design iterations. A concurrent engineering team at GD/EBD, shown in Figure 55, simultaneously develops the product and the related production processes. Sharing knowledge across disciplines and across organizations allows early identification of major cost drivers and allows trade-off studies to optimize the design for acceptable cost. The GD/EBD has established the following fundamental principles for implementing concurrent engineering:

— Empower cross-functional design and build teams.

— Use parallel product and process development.

— Integrate all scheduling.

— Involve customers and suppliers early.

— Minimize life-cycle costs.

— Develop a life-cycle flow chart.

— Develop a risk-management plan.

— Use shared databases to the maximum.

— Establish, collect and evaluate metrics.

To support the conversion to virtual prototypes, GD/EBD has a visualization center composed of a secure network of CAD workstations, computer image generators and a video control center coupled to a wall-sized color projection system. Virtual prototypes can be displayed, manipulated and modified rapidly as an integrated design team sorts out major issues. One significant benefit of the virtual prototype is the ability to electronically check for interferences; i.e. two components occupying the same space. Because it is difficult to check for physical interferences using flat 2-D paper drawings, expensive physical mock-ups must be built to exact specifications to detect interferences. Under the new design approach, as design issues are resolved, changes are made to a central database in accordance with an approval procedure that maintains configuration control. Detailed designs are then created by each discipline and brought to the next team meeting.

This cycle of iterative design work continues until the product converges to an acceptable solution. The success of this design approach is illustrated by the following results:

— A 30 percent cost reduction in the design process due to decreased cycle time

— Simplified designs, welding requirements and pipe layout

— Better tool design; tools can get into tight spaces during manufacturing and assembly

— Properly sequenced plans for manufacturing assembly

— Weight study preparation time reduced by 60 percent compared to manual methods

— Standardized fasteners with a reduction in variations of 62 percent

— Early make-buy decisions

— Overall schedules and management of critical paths enhanced

—Estimates for component lead times improved.

In addition, specific information can be extracted from the parts based global database to satisfy different requirements. Drawings by discipline can be generated with little or no manual intervention, and multidiscipline packages for each module or section can be assembled. Remote terminals can be located at manufacturing sites for easy reference to data and for visualization of the product or the assembly process. Finally, a virtual prototype or electronic mock-up can be generated from the database at a much lower cost and much more precision than a physical mock-up.

SIKORSKY

Sikorsky Aircraft, a division of United Technologies, is located in Stratford, Conn., and is one of the major helicopter producers in the world. In addition to being the prime contractor for the Army's Blackhawk, the Navy's Sea Stallion, and the Marine Corps' Super Stallion helicopters, Sikorsky is one of the leaders of the Boeing Sikorsky Team that won the demonstration and validation contract for the Army's newest helicopter, the RAH-66 Comanche. The Comanche is a twin-turbine, two-seat helicopter that is being designed to perform armed reconnaissance, light attack and air combat missions. The current funding estimate for the 1991-97 demonstration and validation prototype program is approximately $1.97 billion and three flyable proto-

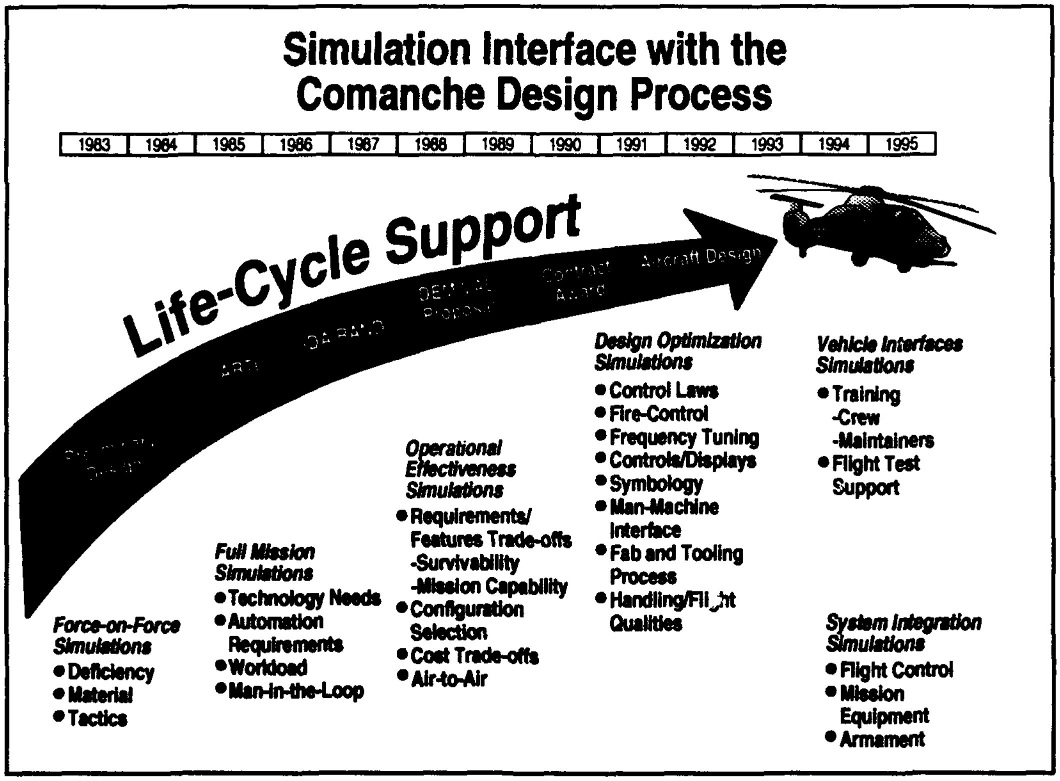


Figure 56. **Use of Simulation on the Comanche Program**

types are being designed, built and tested during this phase. The Comanche is the centerpiece of the Army's new Aviation Modernization Plan that was released early in 1993. This plan reflects the Army's new post-Cold War strategy to react to regional conflicts by using fewer personnel and long-range, self-deployable aircraft that are based in the continental United States. Key design features of the Comanche include low observables, improved sensors, increased maneuverability, agility and speed, and reduced supportability requirements. The Army intends to use the Comanche to replace nearly 3,000 obsolete AH-1, OH-6 and OH-58 attack and observation helicopters.[10] A full-scale mock-up of the Comanche is shown in Color Plate 5.

Sikorsky has made extensive use of simulation on the Comanche program and will participate in the 1993 demonstrations of the electronic battlefield being planned by DMSO and STRICOM. Sikorsky has connected its piloted simulation to SIMNET and will use this medium to engage in simulated battle with other weapon systems. In Figure 56, Sikorsky highlights the past and proposed uses of simulation in the Comanche life cycle.

The Comanche simulation facility capabilities are extensive and extremely impressive. The facility represents an investment of approximately $25 million. The equipment is state of the art with a visual simulator that uses a large number of parallel processors to minimize time to compute the visual scene. There

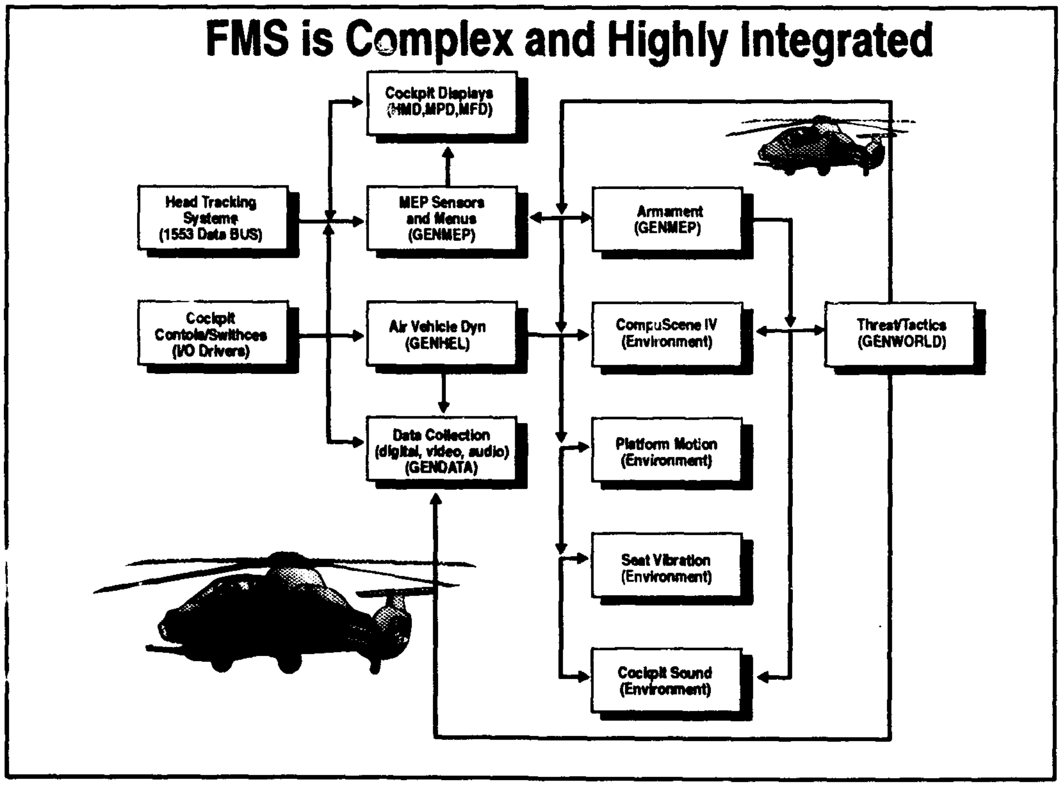


Figure 57. **Comanche Virtual Prototype Subsystem Integration**

is no percetible lag between a control movement and a change in the visual scene. Figure 57 illustrates the complexity and highly integrated nature of the Comanche Full Mission Simulation (FMS). The FMS is a high-fidelity representation of the aircraft design, including the air vehicle, mission equipment payload and armament, that operates in real-time as a crew-in-the-loop simulation. The simulation contains interactive software on board the aircraft to simulate locating threats and being located by threats. Appropriate stimuli are included also to address crew workload requirements such as radio communication and team coordination in mission-oriented scenarios. The simulation includes many facets of a mission like weather effects, time of day, and subsystem conditions. The simulation facility also includes a data collection capability for recording parameters of performance and effectiveness.

The simulator supports design iterations of the crew station cockpit by being able to evaluate the performance of prototype designs in a realistic environment. It will be used to develop flight control laws and assess aircraft-handling qualities with respect to specification requirements. Additional uses include generation of data to support tradeoff studies and defining the detailed elements of the pilot vehicle interface specification. Human factor assessments of crew workload in mission-oriented scenarios will be supported by this facility as well. It will be used for verification and validation of the flight control computer software, training of Army and contractor pilots and for prototype flight test development. As described above, Sikorsky and the government intend to make maximum use of the Comanche virtual prototype during the development process. Figures 58 and 59 illustrate the projected cost benefit relationship of simulation in the Comanche program.

Sikorsky, like other major airframe manufacturers, uses CAD/CAM tools and has experience with digital design techniques. According to Sikorsky's program manager for

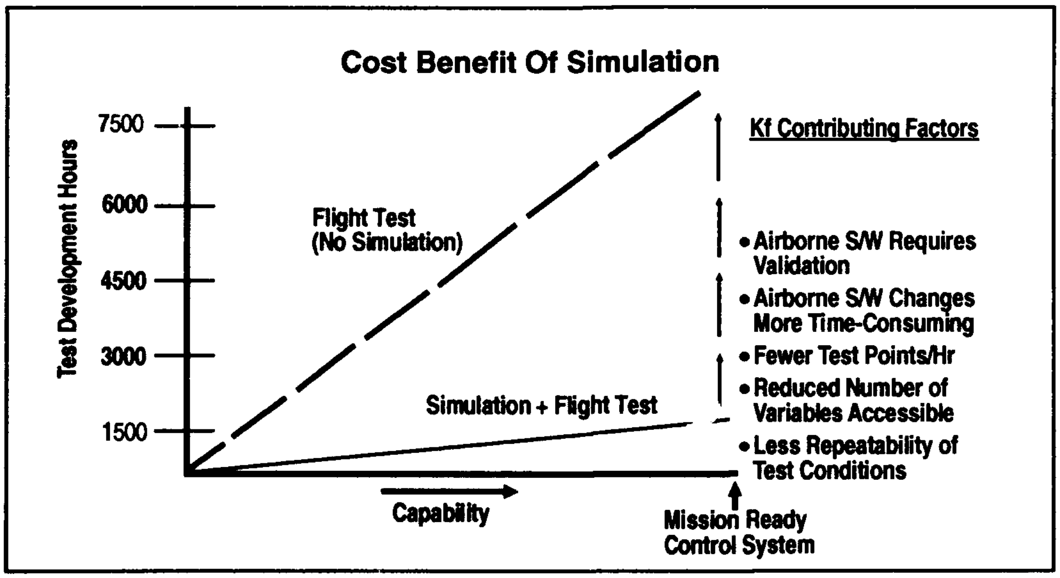


Figure 58. **Comanche Simulation Cost-Benefit Relationship**

the Boeing Sikorsky Comanche Team, "There isn't a drawing board in the building. Everyone is designing things on tubes." [11] Sikorsky is one of the first companies to rely almost exclusively on IBM workstations instead of using mainframe computers to run CATIA software. Joseph Piteo, director of engineering automation at Sikorsky, believes that engineers on the Comanche are "accomplishing things with computer technology that simply could not be done with traditional methods. The full-scale electronic mock-up of the aircraft, for example, could never have been done as thoroughly in aluminum and steel or updated with such ease in real time." [12]

Concurrent engineering is being employed at Sikorsky and the digital design process now allows engineers to go through numerous (50, for example) design iterations where previously they were restricted to doing just a few, using traditional methods. Eugene Buckley, Sikorsky President and Chief Executive Officer, believes this design capability provides engineers with a way to minimize their designs cost and also reduce the manpower required for design production. According to data from the CH-53E Super Stallion program, it took 38 draftsmen approximately six months to produce the working drawings of the aircraft's outside contours. The same task on the Comanche program can be accomplished by one engineer in one month. In addition, precisely designed parts go together well the first time and thus require a minimum amount of rework. Sikorsky's faith in workstations is illustrated vividly by the fact that 1,700 of the 2,500 engineers already have a workstation or personal computer on their desk.[13] The following pictures illustrate Sikorsky's use of these design tools.

Another key feature of the computer capability being employed by the Boeing Sikorsky Comanche Team is the ability to electronically pass designs between the various team mem-

Cost Benefit Of Simulation

Design/Test Area	Simulation Test Hrs	*Kf	Flt Test Hrs	$ Savings
Crewstation	2000	1	2000	103M
MEP Integration	500	2	1000	59M
Flight Controls	1500	5	7500	447M
Airworth. Qual.	500	2	1000	59M
Training	90	1	90	5M
COMANCHE COST SAVINGS RESULTING FROM SIMULATION				$673M

*Kf = Equivalence factor to translate simulator hours to flight test hours

Figure 59. Projected Comanche Simulation Cost Savings

bers. Design changes for subsystems and components being developed by subcontractors are transmitted daily, reviewed by the responsible Sikorsky engineer, and then entered in the computer. Electronic copies of all changes are sent also to all departments involved with the item being changed. Figure 60 shows a Sikorsky engineer reviewing a design change received from Westinghouse.

On the Comanche program the Army has a "one-deep" maintenance requirement that mandates subsystems and components can be installed only one deep so maintenance personnel can reach one item without having to remove another first. Sikorsky successfully demonstrated that it meets this requirement by simulating the removal of a box using CATIA. This visualization capability with the virtual prototype allows maintenance considerations to be incorporated in the preliminary design phase. The Comanche will be maintained in the field using the same software that is being used to design the aircraft. Maintenance manuals will be stored on the aircraft computer. 14

Because the design is digital, the manufacturing engineering department at Sikorsky also is able to begin tooling design efforts early by utilizing the latest design configuration for a particular part from the CATIA system. The CATIA allows the engineers to check for interferences and adjust their designs accordingly. Sikorsky, in conjunction with their Pratt & Whitney sister division, also has the capability to generate a solid model of a part based on CATIA data. The CATIA information is sent to the stereolithography machine located at the sister facility and the next day the engineer has a solid part for design confirmation. Stereolithography has been used also to develop a scale model of the helicopter that was

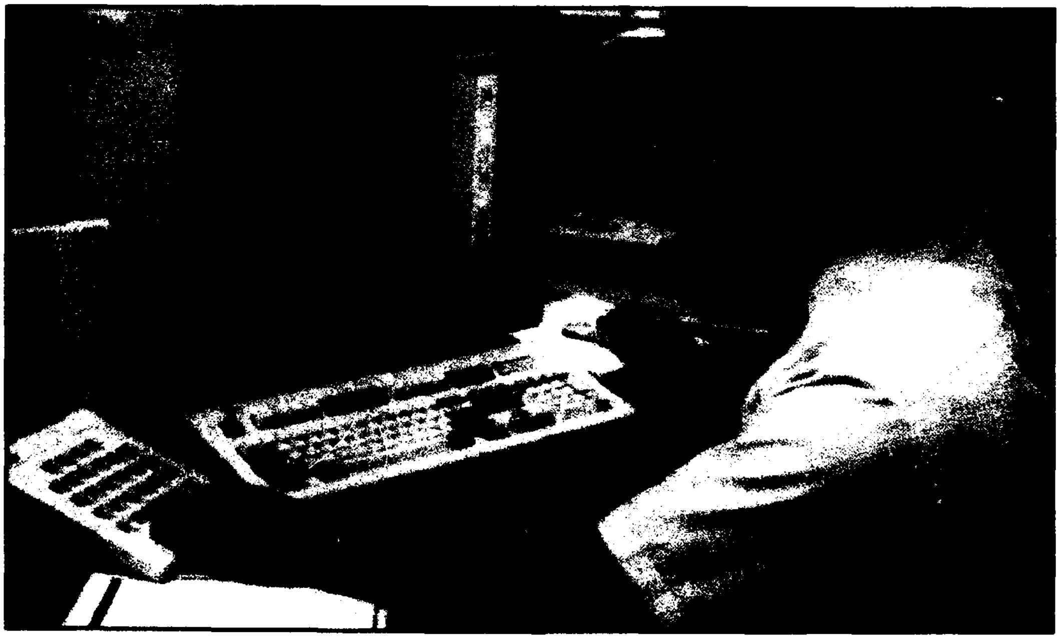


Figure 60. **Sikorsky Engineer Reviewing Design Update**

then coated with metal and used in radar cross-section evaluations.[15]

Another key computer-based design tool being used at Sikorsky is Pro/Engineer. According to their director of engineering automation, this system represents the most advanced CAD technology available. It allows the engineers to build things parametrically. Design iterations and changes can be incorporated even faster than they could in the nonparametric world. The engineer changes a value and the computer takes over and draws the new revised design. Sikorsky is planning on increasing their number of Pro/Engineer workstation seats and their CATIA seats to 180 positions each.[16]

Sikorsky plans to use the same digital design capabilities used for the Comanche program on future commercial ventures. The five or six years it once took to design and build an aircraft can now be compressed into two or three years, and the RAH-66 could be done faster if there were no annual budget constraints. Sikorsky plans to build a commercial helicopter, the S-92, and they believe that within two years after the design effort begins, the S-92 could be flying and it could be certified within three years.[17]

Based on our observations at Sikorsky, technology needed to create virtual prototypes is available and the potential benefits are constrained only by the imagination of those involved in its use.

KOHLER

Kohler is one of the nation's largest privately held companies producing enameled cast-iron and china plumbing fixtures; faucets and fittings; spas and leisure products, generator sets and switchgear; and, engines designed for worldwide applications. The engine division produces small four-cycle engines as

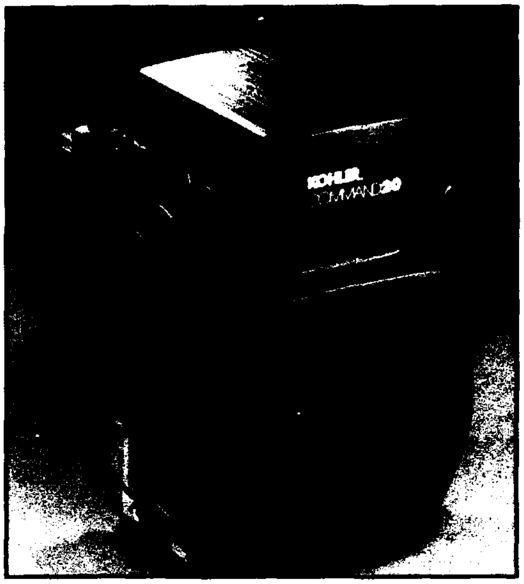


Figure 61. **Kohler Engine**

shown in Figure 61. They range in size from 5-25 horsepower. Located at Kohler, Wis., the company is a small player in a big field. Their strategy is to sell engines offering superior performance and high reliability at a premium price. The company has been enormously successful. Their record speaks for itself:

1. John Deere selected Kohler engines over its previous supplier, Kowasaki, for its large lawn tractors.

2. Market share has grown significantly over the past several years.

3. Manufacturing cycle times have been cut by two years.[18]

4. Physical prototypes are no longer necessary.[19]

5. Kohler offers a 2-year warranty — the longest in the industry.

New engine designs are radically different from earlier versions. They incorporate a slant cylinder for better balance and lower vibration and use a metric configuration for worldwide application. The company attributes their success to the application of computer simulation of product components and systems, largely in the preliminary design stages, due to the versatility of computer models. Like Boeing, their transition to digital design was slow; however, once in place, they reaped a significant competitive advantage.

When the company started using computer-aided design and analysis tools eight years ago, they spent two years of a four-year product-development cycle designing and testing prototypes. Two prototype iterations generally were required — the first to identify flaws in the initial design and the second to prove the flaws had been corrected. Once complete, the company started production. Now, Kohler starts to build its tooling for a new engine as soon as the computer analysis validates the design. They have found the construction of prototypes is unnecessary due to the accuracy of the computer models. As a result, they have cut an average of two years off the product development cycle. According to Kohler's manager of advanced engineering, "The name of the game is getting products out the door faster. Physical prototyping is like doing the job twice. Even eight years ago it was pretty clear that computer simulation of engines was the way to go." [20]

The company uses solid modeling to perform stress, thermal and vibration analysis. Their specific tools include Unigraphics solids models that are transferable for finite element analysis. Their finite element software models are created using Patran from PDA Engineering, and I-Deas from Structural Dynamics Research. A visualization of computer analysis of engine components is shown at Figure

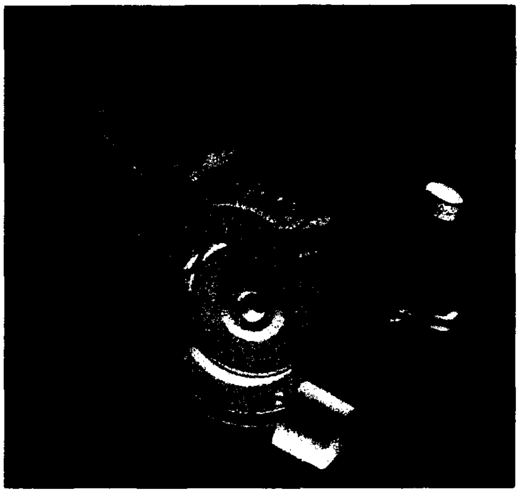


Figure 62. **Computer Visualization of Engine Parts**

62 and Color Plate 6. One of the challenges confronting design engineers is validating models. At Kohler the principal problem was ensuring that the material properties in the model represented the physical properties of the product. It took them several years to conduct testing to verify their database. Once established, they have found that in certain circumstances virtual prototyping produces more accurate results than physical testing.[21] They have found that engineering intuition is not always right. Their software tools have produced designs that they never would have investigated if physical prototyping was required.

NASA/AMES RESEARCH CENTER

Simulation has been a way of life at the NASA/Ames Research Center for many years and because of this rich history, it was high on our list of places to visit. Located within the NASA compound is a three-level circular building housing a joint project of the U.S. Army Aviation and Troop Command and the NASA/Ames Research Center. The Army efforts are under the direction of the Aeroflightdynamics Directorate. The Army and NASA

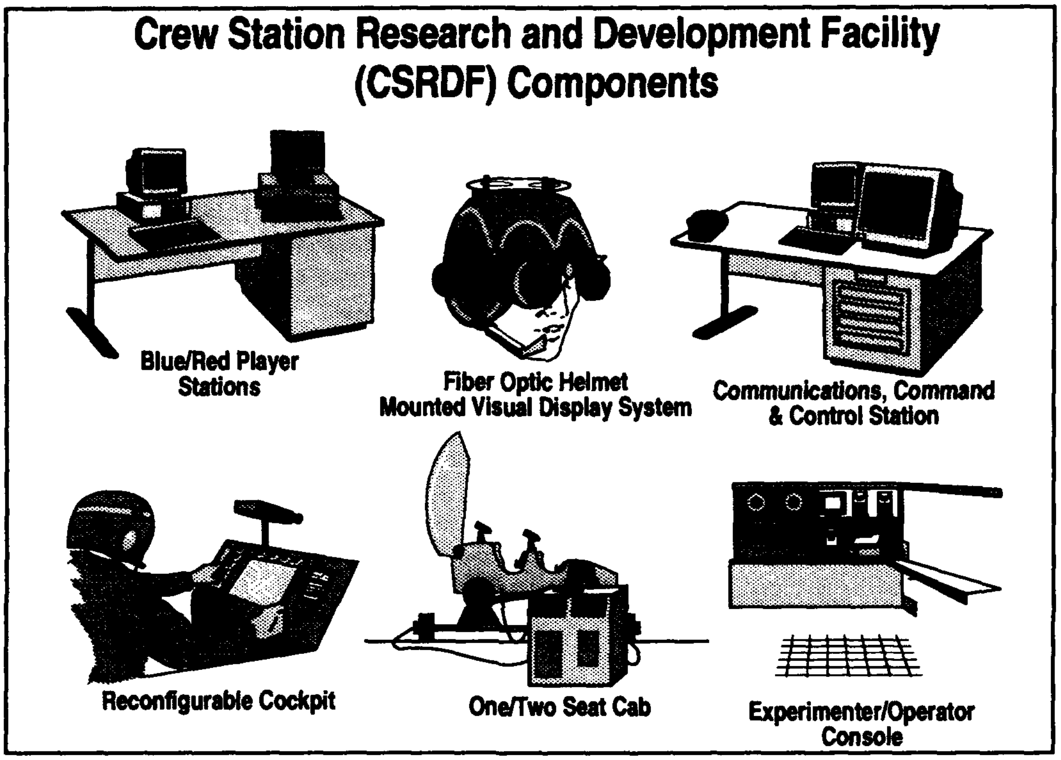


Figure 63. **Major CSRDF Components**

selected this site for its Crew Station Research and Development Facility (CSRDF) because Ames is NASA's lead center for rotary aircraft, human factors and artificial intelligence — three areas considered key in providing a simulation capability to support preproduction research for the next generation of military aircraft. Mr. Gossett, Chief of the Aircraft and Simulation Division, was instrumental in establishing the CSRDF and his 1988 vision of the facility is appropriate, "We're trying to make this a great facility for systems integration, where different hardware and ideas can be put into place, rapidly reconfigured and checked out. If we do it constructively, then we can bring everyone involved here to see how it works." The Army's Science Advisor, the Military Deputy to the Army Acquisition Executive, and more than 100 senior personnel recently visited the facility in the four-day period preceding our trip, attesting to the success of the CSRDF. The jointly sponsored CSRDF facility contains some of the world's most sophisticated simulation hardware. Figure 63 highlights the major components in the CSRDF, and Color Plates 7 and 8 depict the actual equipment.

The first target program for the CSRDF was the Army's Light Helicopter Experimental (LHX) which has since progressed to the Demonstration and Validation phase and now is known at the RAH-66 Comanche armed reconnaissance helicopter. The CSRDF full mission simulator was used extensively in the preparation of specifications for the LHX/Comanche program. Every functional subsystem in the aircraft is contained in the

CREW STATION RESEARCH AND DEVELOPMENT FACILITY

OBJECTIVES

- Gov't development of engr specs for advanced rotor craft
- Examination of PVI/advanced MEP issues for advanced rotorcraft
- High fidelity aviation node in Defense Simulation
- Internet to support:
  - Advanced Tech Demos
  - S&T Thrusts
  - TRADOC War Games
  - DARPA Programs

CAPABILITIES

- Comanche Baseline
- Full Mission Equipment Models
- 200 Interactive Combantants
- Fiber Optic Helmet Mounted Display
- Rapidly Reconfigured Cockpit
- High Fidelity Visual & Math Models
- Interactive Tactical Environment Software
- Distributed Simulation Environment

SIMULATIONS COMPLETED TO DATE

- Comanche Training
- Aided Target Recognition PVI
- Helmet Mounted Display Technology
- Integrated ASE PVI
- Stereo HMD Display Requirements
- Obstacle Avoidance PVI

PLANNED ACTIVITIES

CSRDF-AVTB Networking	1-2 QTR FY 93
MASAT-AIR Evaluation	4 QTR FY93
ATCOM/TACOM Joint Exercises	FY94
RPA Developmental/Initial Evaluation	FY94-95
Louisiana Maneuvers	FY95
Joint Precision Strike	FY95
Warbreaker	FY97
Final RPA Evaluation	FY97

Figure 64. CSRDF Program Overview

simulator as well as every other system the Army crew might encounter in an actual mission, both friendly and hostile. The database includes vehicles, communications, jammers weapons, as well as the tactics that might be employed on a given mission. According to views expressed in 1988 by the Chief of the CSRDF, the biggest challenge facing the Army on this program was to determine if the "pilot can do the job the user wants?" Since its inception, the simulator at the CSRDF has played a central role in resolving such issues. The chart shown in Figure 64 delineates the current objectives, capabilities, accomplishments and planned activities for the CSRDF.

The Rotorcraft Pilot's Associate program (RPA) and the Battlefield Distributed Simulation - Developmental (BDS-D) program are two major efforts the CSRDF is supporting. Joint exercises will also be supported via the Internet. Figure 65 shows the test bed connectivity for these programs and exercises.

The Army Chief of Staff tasked the Army Materiel Command and the Army Acquisition Executive to "exploit advanced distributed simulation to improve acquisition from concept to fielding." Figure 66 provides an overview of the future envisioned by the Army's leadership. The electronic battlefield is at the center of this new *electronic Army* and the CSRDF has been designated to be a key player in the evolutionary accomplishment of this task.

ADVANCED RESEARCH PROJECTS AGENCY (ARPA)

The ARPA, formerly DARPA until 15 March 1993 when "Defense" was dropped from its name, has many projects focused on improving the ability of the defense industry to pro-

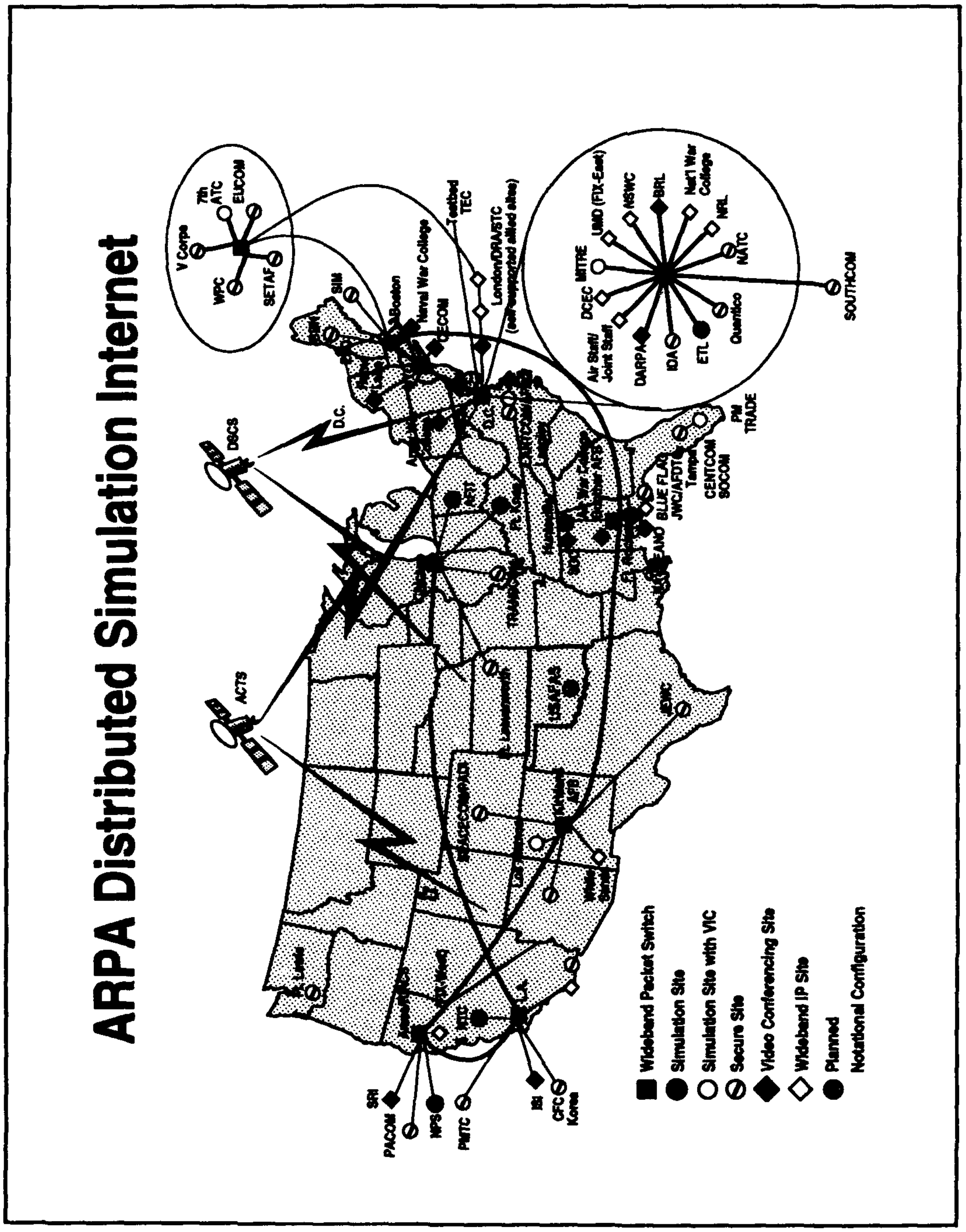


Figure 65. **Internet Communications for DIS (Source: ARPA)**

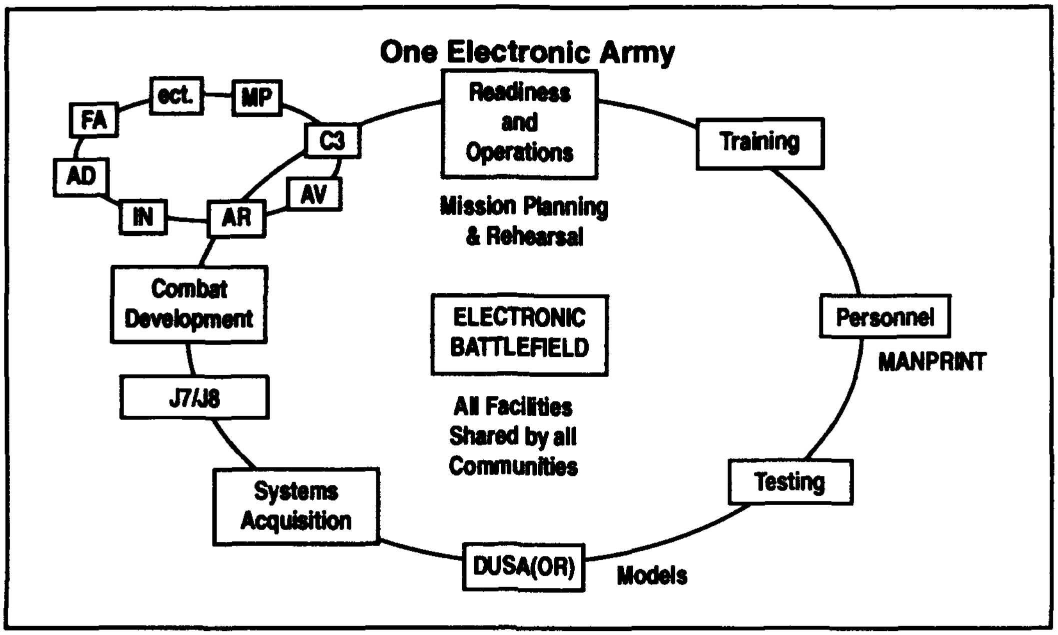


Figure 66. **Army Vision of the Electronic Battlefield**

vide the latest technologies, efficient processes and cost-effective products to the Services. The agency's $1.5 billion FY 1994 budget includes funding for industry research to develop and demonstrate advanced information technology to support integrated product and process development, agile manufacturing and continue the War Breaker simulation program. These efforts are related directly to synthetic environments, virtual prototyping and the acquisition process.

The Manufacturing Automation and Design Engineering (MADE) program at ARPA seeks to focus information technology on applications in concurrent engineering, flexible manufacturing and electronic commerce. Structured as a three phase program, the MADE objective is to develop an integrated design, analysis and manufacturing control prototype software environment supporting full life-cycle acquisition by 1996. Phase one of MADE was initiated in 1992 with several contracts to construct the generic software building blocks for design tools and design process management. Extensive use of simulation and visualization is planned. Phase two includes building application level tools.

Designing for assembly, assembly process simulation, tolerance synthesis, design, reuse and modification and designing for rapid tool setup and changeover will be demonstrated in the flexible manufacturing of infrared focal plane arrays and sensor packages. Flexible factory concepts will use low-cost modular equipment, a wafer cassette process that eliminates the need for a clean room and intelligent manufacturing process control systems. Advanced Technology Demonstrations (ATD), supporting S&T Thrust Seven, are proposed for phase two. Phase three will consist of a series of demonstrations to prove the success of an industry-wide distributed flexible manufacturing infrastructure.

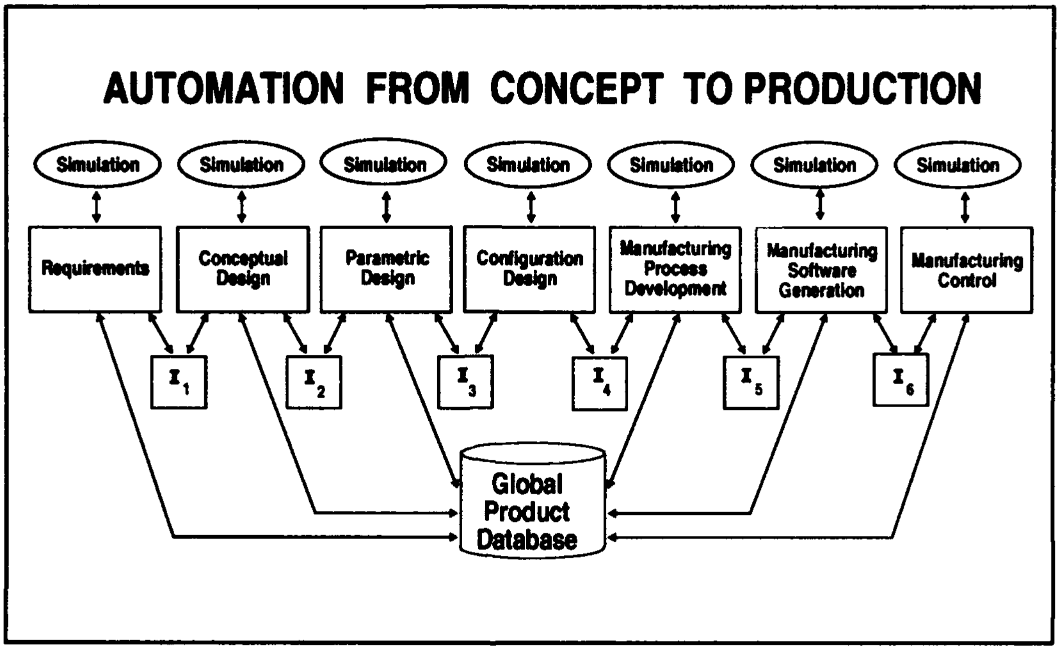


Figure 67. **MADE Program Will Develop Interfaces Between Processes (Source: ARPA)**

The MADE program is expected to pay off with a major reduction in acquisition cycle time, facilitate a surge in production in time of war and allow rapid fielding of the latest technology. Figure 67 shows the steps in the design process from requirements definition to manufacturing. Specialized software tools, usually operating in isolation, are employed at each step in the process and design information is passed along the process across interfaces (represented by I1 to I6).

Unfortunately, many of these interfaces are not fully automated and require significant manual reformatting to provide usable inputs for the next stage. The ARPA is working on standard languages to improve information exchange. Simulation is used at each step to accomplish design goals. Finally, the results of the design process are held in a global product database available to all participants.

There are numerous benefits to using information technology as the MADE program envisions:

—Easy flow of information between steps in the process supports an iterative approach to designing. Cycle time is decreased; thus, designs can be refined to a higher degree of accuracy in the final product and rework is reduced significantly.

—Geographically dispersed organizations can participate in the design process over wide area networks.

—Well-defined interfaces between steps in the process allow easy removal and replacement of each software process as new programs are developed. This can be accomplished with no disruption to the overall design process.

— With standard interfaces defined, many companies will have the ability to enter the design process. Competition is enhanced in industry when many companies can participate in the design effort electronically.

A second significant program at ARPA from the perspective of this report is the War Breaker simulation. War Breaker develops and demonstrates the capabilities of an integrated system that detects, identifies, targets and neutralizes time-critical targets. Focusing on key ARPA technology developments and service initiatives, War Breaker is coupled closely with the Precision Strike, Global Surveillance, and Communications Science and Technology Thrusts. Using distributed interactive simulation, War Breaker has the capability to visualize and communicate system performance and requirements using man-in-the-loop interactive simulation. War Breaker supports bench testing of sensors and software, and modeling and flight testing of full weapons systems. Additionally, the War Breaker simulation environment will be used as a system engineering tool to identify, define, verify and validate system requirements. ARPA states that:

> *Emerging simulation technologies could be applied to system engineering and acquisition issues, including evaluation of a proposed system's measure of effectiveness at the theater level; feasibility assessment of hardware and software at the component level; and development and testing of weapons systems.* [22]

War Breaker is an excellent example of using synthetic environments and virtual prototypes to determine system requirements. Critical design issues can be investigated in detail. This is especially important for problems which require a high degree of human interaction from among diverse organizations participating with multiple weapon systems.

A third significant program at ARPA is aimed at revamping the Navy's ship and submarine design process. Recently, ARPA awarded contracts for the initial 18-month phase of a program to "link geographically disparate design teams by high-speed networks so they can exchange their ideas in real time and use virtual reality technology to model and test their work before a prototype is ever built." [23] Expectations are that the time to design a ship can be cut in half — without using a physical mock-up and with increased quality.

U.S. ARMY NIGHT VISION AND ELECTRONIC SENSORS DIRECTORATE

Efforts are underway at the U.S. Army's Night Vision and Electronic Sensors Directorate (NVESD) to develop what may be the world's first synthetic infrared target environment that is realistic and scientifically accurate. This infrared model capability is being pursued to support programs such as Comanche and Apache Longbow that need a high-fidelity simulation which can be used to evaluate the Automatic Target Recognition (ATR) algorithms associated with sophisticated multi-sensor configurations. The NVESD infrared simulations are produced by the Visionics and Image Signal Processing Division and their software product, NVSIM, will be available to the Forward Looking InfraRed (FLIR) community. [24]

Commonly referred to as the Night Vision Laboratory, NVESD has extensive experience developing infrared scale models and terrain boards used in various infrared simulations. The physical terrain board, shown in Figure 68, is used with many different infrared scale models to create scenarios which support a variety of applications. Figure 69 is an infrared picture of a scale model tank taken on the physical terrain board. The NVESD has an extensive library of infrared pictures and infrared video that depict military equipment and typical background topographies. The

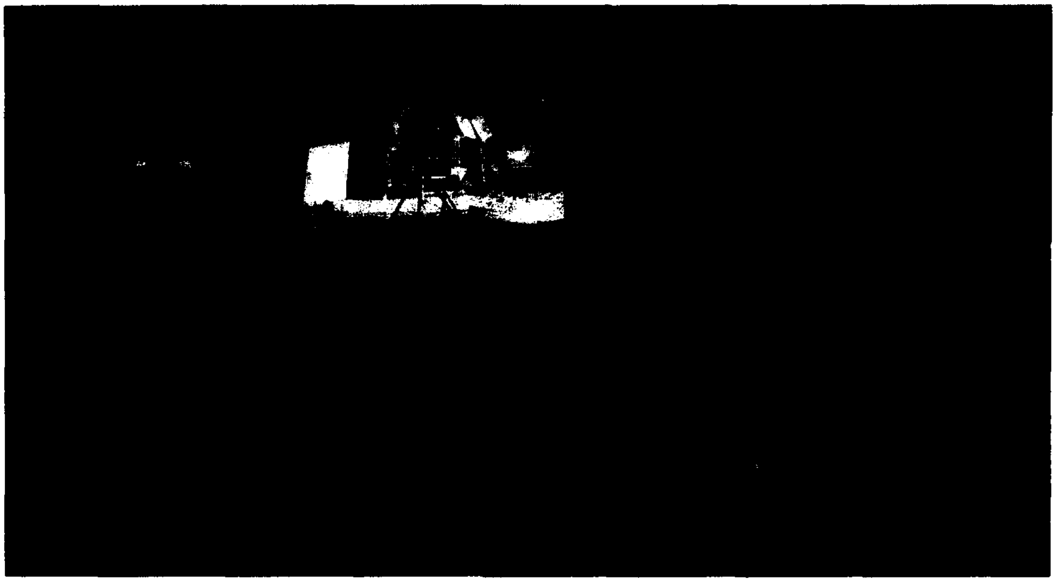


Figure 68. **NVESD Physical Terrain Board**

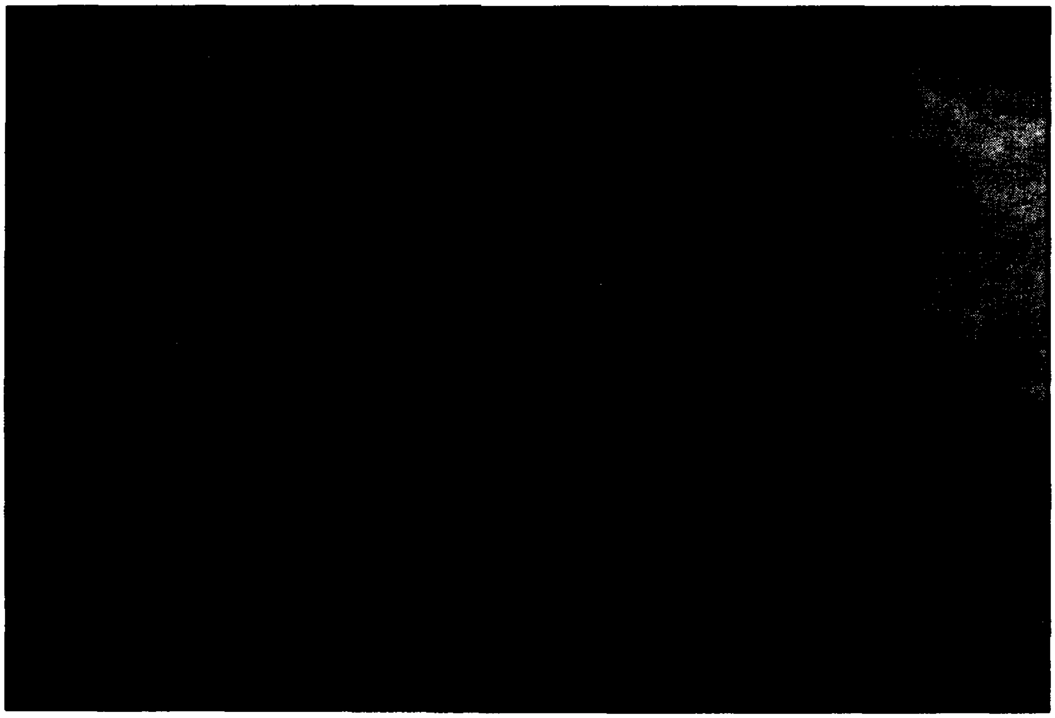


Figure 69. **Infrared Picture of Thermal Tank Model**

pictures and video tapes are used in simulations that are programmed against a specific scenario; for example, if a tank drives in one specific direction at a specified time of day, the imagery displayed can be preselected to provide a realistic view of the tank's target and the terrain over which the tank operates. The ability to combine the infrared library with infrared target imagery on the terrain board has enabled NVESD to accommodate numerous user, developer and tester needs.

But, there are significant limitations that are well documented, such as the lack of atmospheric effects and the inability to simulate anything other than forward looking infrared (FLIR) and television sensor systems. To overcome these shortcomings and to meet the new requirements associated with multisensor platforms, NVESD is developing a state-of-the-art digital model of an infrared battlefield environment. [25]

This new capability will have the potential to support the emerging soldier-in-the-loop weapon system simulations that will soon be used to make critical major weapon system acquisition decisions. These new simulations are totally dynamic and the weapon system driver and/or the gunner have the real-time ability in the simulator to view, drive and fight in all directions at any time of the day or night. If realistic evaluations are to be performed on the ability of the operator to detect targets with virtual prototypes that contain new sensors, a high-fidelity virtual prototype of the infrared environment that the sensor can see must be developed. The NVESD is addressing this challenge in an incremental approach that allows it to take advantage of the advancements in computer technology continuously.

To develop a digital infrared environment, massive computer power is required to portray realistically the infrared signatures of every feature in the field of view. This is especially true for scenarios that portray different types of weather at various times of the day or night. Since this is an infrared domain, every object in the camera's field of view (the digital environment) has a unique signature which changes based on the angle from which it is being viewed. The signature is composed of thermophysical properties such as reflectivity, emissivity, thermal conductivity, density and specific heat. [26] The camera's picture presented to the operator must also be adjusted by the computer to account for factors such as the field of view and the impact of platform vibration on the sensor.

This is no trivial task and only until recently could modeling be attempted for anything more than selected targets or selected samples of vegetation, and even this limited sample could not be done in real time. With recent dramatic increases in computer processing power, the prerequisite computer capability to expand these single targets and backgrounds into an infrared environment finally has become available. If the ever-increasing performance trend in computers continues, it may be possible to develop, before the end of the decade, a fully dynamic infrared environment for use in real time soldier-in-the-loop simulations.

During our visit we observed the significant progress the Visionics and Image Processing Division personnel have made in developing digital infrared models of military equipment, trees, and other types of vegetation. It is important to note that NVSIM is being developed around modular programming techniques to facilitate the incorporation of additional sensor effects as they become available. Selected sensor effects can also be included or excluded at run time. The NVSIM is written in standard ANSI C programming language and uses a UNIX operating system to make it portable to most modern workstations. [27] Fig-

Figure 70. **High Fidelity Digital Terrain Board (Source: NVESD)**

ure 70 illustrates their current ability to generate impressive high fidelity scenes for the digital terrain board. Although the ultimate real-time digital infrared environment is far off, significant steps are being made and could be accelerated if additional resources were committed to this promising effort.

ACADEMIC RESEARCH

University of North Carolina at Chapel Hill

The facility which houses the computer center at the University of North Carolina (UNC) at Chapel Hill existed in cyberspace before it was actually constructed. The virtual version of Sitterson Hall allowed people who were going to work in the building to "walk through" the model in cyberspace. Many of them felt that one particular feature in the lobby created a cramped feeling in a busy hallway. The architects didn't agree until the future occupants used the 3-D cyberspace model to give the planners a chance to "walk through" themselves. As a result, the partition was moved, the building constructed, and there is no feeling of being cramped in the physical lobby today. The UNC facility is quite impressive. While at UNC, we saw graphics displays generated by their Pixel-Planes 5 multicomputer, used their head mounted display and stereoscopic displays to "walk through" a virtual kitchen and used their Argon Remote Manipulator (ARM) in an attempt to dock molecules. The following paragraphs discuss each of these three capabilities.

The Pixel-Planes 5 multicomputer system rendered the highest quality graphics of all the locations visited. The topography looked exactly like a photograph taken with a high-powered lens. It was as close to real life as one can expect. The system consists of a

Graphics Processor, a Renderer and a Ring Network.

The Graphics Processor is general-purpose and math-oriented and carries out geometric transformations and other scaleable calculations. It is a powerful, math-oriented computing node based on the Intel i860 microprocessor. Renderers, fine-grain, massively parallel arrays of processors based on custom logic enhanced memory chips, perform most pixel-oriented calculations in parallel. It employs a novel approach to graphics image generation in which the transformation engine specifies the objects on the screen in pixel-independent terms, and the Renderer works from the description to generate the final image.

The Ring Network moves data and control messages between system components at high speed. It links the parts of the system, moves object descriptions and pixel data between components, and provides the considerable bandwidth needed to take full advantage of the performance of the parallel Graphics Processors and Renderers. The Ring operates at an aggregate data rate of 160 million 32-bit words per second, supporting eight simultaneous data streams between Ring ports at 20M words per second (32-bit words). The machine rapidly renders polygonal images with advanced lighting models and textures, directly renders spheres as well as objects described by constructive solid geometry, performs near real-time rendering of volume data sets modeled as transparent gels, and executes a variety of image-processing algorithms. It is modular and can be configured in a variety of ways to trade cost for performance. Pixel-Planes 5 is an example of a multicomputer, a class of parallel machines that has multiple computing nodes, each with its own memory system.

We walked through a virtual kitchen and opened cabinet doors utilizing a HMD and the head-tracked stereoscopic displays. To achieve this effect, the computer must constantly receive information about the precise position and orientation of the user's head and must respond immediately to all changes in head position by adjusting the displayed images appropriately. The head-tracker project at UNC investigates and develops methods for this position tracking. Their immediate goal is to develop optical head-tracking technology that will function within a room-sized environment and be accurate within 1-2 mm and 0.1 degrees.

We used the system that utilizes an optoelectronic tracker. The system features light-emitting diodes (LEDs) mounted in the ceiling of a room and imaging sensors, based on lateral-effect photodiodes, mounted on the head of the HMD (see Figure 71). Color Plate 9 shows a user with the HMD in the virtual kitchen and the view the user sees. In operation, as a HMD wearer walks beneath the ceiling, a real-time multiprocessor system computes the position and orientation of the user's head. One 68030-based processor finds the set of LEDs in each sensor's field of view, illuminates the appropriate LEDs according to an LED driver and extracts photo coordinate data from the image sensors. This process is complicated by the fact that as the HMD wearer moves, the sets of LEDs change constantly. To their knowledge, this is the first demonstrated scaleable tracking system for HMDs, meaning that to cover any room size, one need only add more panels to the ceiling.[28]

We also wore 3-D glasses and the ARM in an attempt to dock chemical molecules. These tools are a way of using highly refined capabilities of the human haptic system to explore chemical bonds. Users, navigating in three dimensional space, move strings of molecules

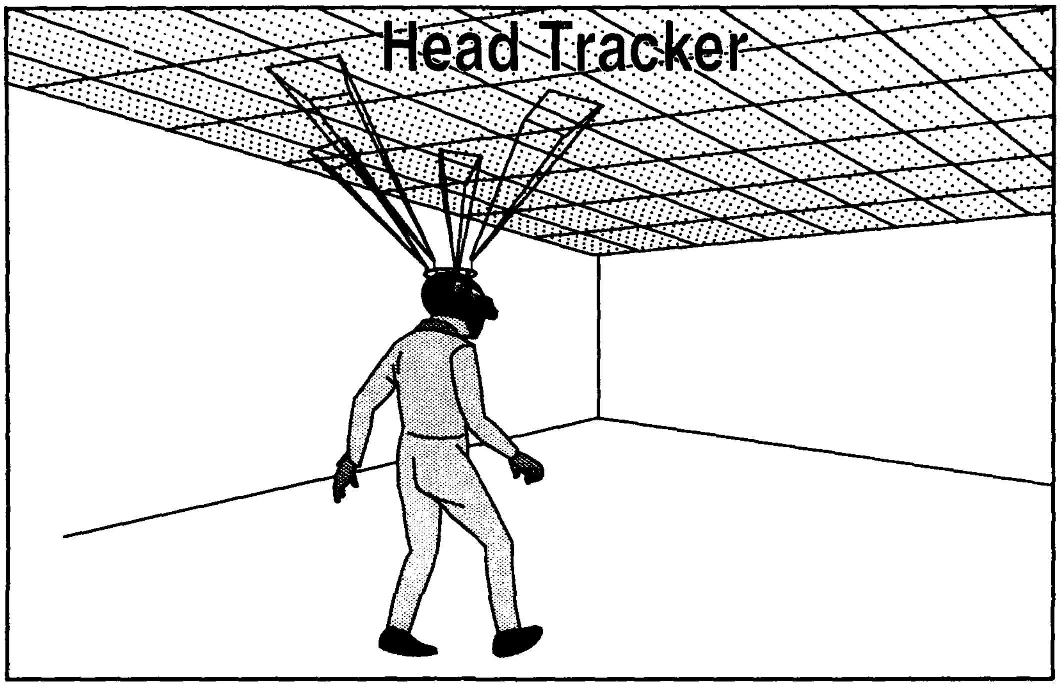


Figure 71. **Room-Sized LED Tracking System**

in various directions to mesh with other molecules. As assessed by one of the Fellows: "At first, I felt as if I was wrestling with the ARM as I tried to twist, jam, rotate and extract molecules, unsuccessfully may I add. Once I felt comfortable with the system, however, it worked easily and I was able to move objects around freely with little difficulty." Color Plate 10 shows an operator immersed in molecule docking. Harold Rheingold described the experience as:

> *Knowing next to nothing about the chemistry symbolized by the colored clouds floating in virtual space and the tinkertoy bonds that I could feel in my arm bones, I was able to find my way into a place where the ARM resisted at a minimum amount between all its degrees of freedom. It was more like playing a video game or a trombone than any problem-solving I remembered from high school chemistry.* [29]

The Human Interface Laboratory (HITL)

The state of Washington created the Washington Technology Center (WTC) in 1983 as a catalyst for statewide economic development. Its goal is to attract private industry and federal research dollars to help finance commercially promising research at the state's universities. In October 1989, the WTC established the Human Interface Technology Laboratory with the stated objective of transforming virtual world concepts and research into practical, economically viable technology and products. They founded the Virtual Worlds Consortium, consisting of more than 15 organizations, including large corporations like Boeing, Ford, American Express, the Digital Equipment, along with other organizations

like the U.S. Navy and the Port of Seattle. The consortium supports the HITL as a forum for the advancement of virtual worlds technology; for educating professionals, students, and the general public regarding virtual worlds technology; and for enhancing commercial applications of virtual worlds technology. Membership costs participants $50,000 per year and the annual fees are pooled to support selected research. [30]

The Laboratory's core activities include the virtual knowledge interface base (VKIB) and the virtual simulation laboratory (VSL), which support a number of specific projects including the Virtual Retinal Display (VRD). The objective of the VKIB project is to provide a repository for technical discussion, experimental data, research findings, and other information related to virtual interface technology. Current VKIB activities include establishing a comprehensive literature and media collection, hosting the Usenet newsgroup, preparing hard copy newsletters on research developments in virtual reality, and beginning a scientific and engineering journal to disseminate research findings.

The VSL is a unique simulation laboratory incorporating virtual interface controls and displays to support the development of advanced interface concepts. It will be used to investigate the underlying human sensory, perceptual and psychomotor behavior associated with interaction in virtual interface; develop interface devices; explore new virtual interface concepts; and, develop metrics to assess the goodness of the control and display approaches.

The VRD project has great potential. Its objective is to project high resolution color images directly on the retina. The lab plans to commercialize this product and sell it in the mid-1990s for under $5,000. The advantages of the VRD are significant: wide field-of-view, high resolution, small size / weight, low cost and color. Other projects at the HITL include 3-D audio graphics, position tracking, Virtual Environment Operating System (VEOS), virtual prototyping, visualization, televirtuality, education and prostheses research. [31]

One of the HITL's first projects had the potential for commercial application at the Port of Seattle. According to the director of information systems at the Port, there were two reasons the Port was pursuing VR modeling. First, they saw it as a kind of "what-if" machine for port design, running the simulation through different situations to see how the whole system reacts.

The second reason was more compelling; the Port planned to use the model as a communication device with the Port's biggest clients — Japanese, Chinese, Korean and others. They are hopeful that misunderstandings, delays and costs caused by spoken language barriers might be mitigated if engineers, planners and clients on both sides of the Pacific could walk through VR versions of the proposed construction during every stage of the planning process.

The technological applications included being able to walk through a virtual facility, operate cranes from inside ships, and locate equipment — actually operate a facility in the virtual world as if it was a real terminal. Since no other port facility in the world offered such a capability, it would undoubtedly give the Port a competitive advantage in attracting customers. Unfortunately the VR project, envisioned only two years ago, has been abandoned. The primary reason given was that the VR effort was launched too late and the Port's engineers were already too far along in their design efforts to use the VR system. [32]

Other Institutions
Other institutions that shared their time and resources with us were the University of Dayton, the University of Central Florida and their Institute of Simulation and Training, Florida Institute of Technology, and the Air Force Institute of Technology. Their contributions are included throughout this report.

ENDNOTES

1. "Designing Airplanes: Boeing's 777th Heaven," p. 69.
2. "Final Assembly of 777 Nears," p. 48.
3. Lucas. "Designing Airplanes: Boeing's 777th Heaven," p. 70.
4. *Ibid.*
5. "Final Assembly of 777 Nears," p. 49.
6. Rose. "Boeing Names Woodward to be Thornton Heir."
7. "Final Assembly of 777 Nears," p. 50.
8. "Designing Airplanes: Boeing's 777th Heaven," p. 70.
9. Electric Boat Division makes extensive use of computer-aided design tools and has a modern visualization center. The writers do not wish to imply that the existing design process is entirely manual, only that manual processes and physical mock-ups are the starting point for the discussion of PADP.
10. News release, Boeing Sikorsky RAH-66 Comanche Fact Sheet, December 1992.
11. Hughes. "Sikorsky Exploits Workstations in RAH-66 CAD/CAM Design Work," pp. 46-48.
12. *Ibid*, p. 46.
13. *Ibid*, p. 47.
14. *Ibid*, p. 48.
15. *Ibid.*
16. *Ibid.*
17. *Ibid.*
18. Puttre. "Virtual Prototypes Move Along Their Physical Prototypes," p. 59.
19. *Ibid.*
20. *Ibid.*
21. *Ibid.*
22. "War Breaker Simulation Phase One: The Zealous Pursuit Exercise," Defense Advance Research Projects Agency, undated, pg. 2.
23. Varon, Elana, "ARPA High-Speed Network to Revamp Navy Ship Design," 26 April 1993.
24. Horger. "NVSIM: UNIX-based Thermal Imaging System Simulator," p. 1.
25. Der. "A Multi-Sensor Digital Terrain Board for Processor Test and Evaluation," p. 1.

26. *Ibid*, p. 4.

27. Horger, p. 1.

28. "Head-Tracker Research." (University of North Carolina at Chapel Hill, August 1992):1.

29. Rheingold, *Virtual Reality*, p. 28.

30. "The Human Interface Technology Laboratory," pp. 2, 4.

31. "HIT Lab Overview and Projects 1991."

32. Interview, Mr. Cecil Patterson, Director of Information Systems, Port of Seattle, 27 January 1993.

Nothing will ever be attempted if all possible objections must first be overcome.
— **Samuel Johnson**

Chapter 6
CONCLUSIONS AND RECOMMENDATIONS

When we started this research effort, we were skeptical about the usefulness of virtual prototyping in the acquisition process so we set aside the theory and sought out defense and commercial companies, along with universities, that had used virtual prototyping. Our journey took us to large and small companies, some with ambitious virtual prototyping programs and others doing little. It was enlightening to discover that virtual prototyping does, in fact, produce significant and measurable results. We believe it produces a more robust design and significantly reduces costs and product development cycle times. We saw an example of a commercial company that had gained a significant competitive advantage in their market. Virtual prototypes are useful in the design of complex systems like Boeing's 777 and in far less sophisticated items such as four-cycle 18 horsepower lawn mower engines, and for almost everything in between. We believe they can be beneficial in any application involving significant design effort or complex manufacturing that has previously used physical prototypes.

Fundamental changes in the defense acquisition process have increased dramatically the importance of virtual prototyping in the acquisition of new weapon systems. Based on our review of applicable literature, interviews with more than 50 individuals associated with the technology, and visits to more than 25 companies, we offer the following conclusions and recommendations.

CONCLUSIONS

1. In many cases, physical prototypes are no longer necessary. Virtual prototypes, based on CAD/CAM data, are taking the place of physical prototypes. Today's CAD/CAM tools reduce design and manufacturing costs, shorten cycle times, and yield better designs. Industry is placing less reliance on physical prototypes. They have embraced CAD/CAM because of its payback derived from lower manufacturing costs due to fewer design changes — the parts fit together the first time and designs are producible. Design and manufacturing engineers can now assess the feasibility of manufacturing a part and then modify the design or manufacturing processes before actually producing the product.

2. Rapid prototyping greatly accelerates the production of new products. Rapid prototyping techniques are being used increasingly by large U.S. manufacturers. Successful implementation of rapid prototyping requires organizational commitment and the application of several key technologies. Prototypes are a direct link to the production process and can be used to enhance communication with customers and vendors. They can be shown to

customers to demonstrate the physical properties of the product and agree on any desired design modifications before beginning tooling or production. Prototypes also can be sent to vendors of complex parts or subassemblies to assist them in developing an accurate quote.

3. Virtual prototyping can provide a clear, competitive edge to companies who embrace and successfully implement its features. Reduced cycle times provide the opportunity to make new products available in less time and thus permit a company to become a market leader. In addition, companies usually can realize a positive return on their virtual prototyping investment in less than two years. It is an area where dual-use investment has tremendous potential.

4. Virtual reality has great potential, but it is not clear when DOD will be able to benefit from the use of this technology. Visual images in today's head-mounted displays are cartoon-like. Headsets are bulky and have an awkward umbilical connected to the computer that restricts movement. Also, some operators tend to feel sick while using the head-mounted displays. Virtual reality does have tremendous potential in the entertainment industry, and significant investment in this technology is being made to exploit this new capability. Virtual reality applications in DOD will be paced by the speed with which breakthroughs are made in display resolution, computer update speed, and operator mobility.

5. Verification, validation and accreditation (VV&A) of the software used to create synthetic battlefields and virtual weapons systems is a major challenge. Who within DOD has the responsibility for accrediting these synthetic battlefields and weapons systems and how will this be accomplished? Standards are needed and software tools need to be built to facilitate VV&A. Who within DOD has the responsibility for this challenge, and where will the necessary funds be found to support this effort? The responsibility does not appear to be clearly delineated within the DOD.

6. The computing power available today falls short of that needed to produce high quality images for synthetic environments. Implementing a desirable level of realism will require a significant investment in software development. Software development tools needed for rapid construction of battlefield simulations are almost nonexistent. Synthetic battlefields need to look real and they need to present the same environmental conditions to all participants. These environments need to include semiautomated forces which accurately mimic human behavior. Finally, models used to represent realistic human performance and decision making need to be validated.

7. Virtual prototypes can be a valuable tool for program managers to use in identifying and managing program risks. Program managers are required to develop acquisition strategies and program plans that are event-driven and that explicitly link major contractual commitments and milestone decisions to demonstrated accomplishments in development, testing and initial production. At each milestone decision point, assessments are required of the status of program execution, plans for the next phase, and the rest of the program. Virtual prototypes can be used effectively to measure performance against milestone decision criteria. They can be used to test the system or certain high-risk subsystems against certain simulated

threats, assess the effectiveness of the proposed technology and evaluate the feasibility of the design for producibility. Virtual prototypes can be used also to assess the risks inherent in the degree of concurrency being proposed for a program.

8. Major weapon system acquisition decisions in the future will be significantly influenced by the performance of virtual prototypes in synthetic battlefields. The DOD war planners and higher level decision makers will use synthetic environments that employ different weapon systems and different force structures to evaluate their warfighting impact. Inherent in these ongoing synthetic force-on-force evaluations will be the opportunity to insert a new capability via a virtual prototype and evaluate its impact. The ultimate test for each system will be to demonstrate value-added war fighting capability that is significant enough to influence the outcome of a conflict that takes place in a specified battlespace. If a significant warfighting capability is demonstrated, a decision will be made to either upgrade existing systems through incorporation of the technology or to begin the development of an entirely new system based on the virtual prototype's performance during the test.

9. A virtual prototype can influence product support positively, or system advocacy in DOD terminology, at all levels of the acquisition process. Being able to demonstrate the "value-added" capabilities of a new system while at the same time convincing the audience that the technical and financial risks associated with obtaining this capability are reasonable will be essential in future multilayered funding competitions that will exist in the late 1990s. Three-dimensional visualization that can be provided by a virtual prototype also facilitates the introduction of a new weapon system concept and is a means to increase user involvement in the development process by providing a better foundation for user and developer communications.

10. Virtual prototypes enhance a company's competitiveness by giving it a perceptual edge. Virtual prototypes can assist both the contractor and the government program manager in understanding new doctrinal concepts and warfighting impact of new systems. More importantly, it provides a means for the engineers to visualize, maybe for the first time, the interactive results of what previously has been represented by two-dimensional tables of data and thousands of complicated equations

11. Virtual prototypes can provide developmental and operational testers with the ability to conduct meaningful evaluations that can aid in the design of the tests performed during each phase of an acquisition. A virtual prototype that is developed as a scientific visualization in the Concept Exploration and Development phase and is enhanced continuously throughout the development process, can provide the test community with the ability to optimize the number of tests that are conducted as well as reduce the time needed to collect required data. Because virtual prototypes exist in a digital world, the tester will have the opportunity to conduct numerous iterations of the same test scenario and aid in the design of tests performed during each phase of the acquisition process. Substituting a virtual prototype for a physical prototype in all or some portion of the tests which involve destructive testing and fatigue analysis, can allow the tester

to "dry run" test scenarios, optimize tests for a physical prototype, determine practical test limitations and in many cases actually conduct additional tests that may not be affordable without virtual prototypes.

An even more productive and affordable test alternative might be to use virtual prototypes to evaluate the system without building any physical prototypes. Based on commercial as well as military contractor experience, the current virtual prototyping capabilities will eliminate the test community's need for most physical prototypes, especially in the DOD acquisition phases prior to engineering and manufacturing development.

12. Concurrent engineering, when properly implemented, will result in products which incorporate state-of-the-art technology to satisfy customer needs and manufacturing capabilities. It is being used successfully by a growing number of companies, and is a prerequisite to future success. Companies not embracing concurrent engineering during the 1990s may find themselves outdated and producing what the customer no longer wants.

13. Successful implementation of virtual prototyping requires a commitment from senior management. Converting to digital design concepts is a major cultural change for most companies and, as such, requires top-level commitment to see it through the conversion process.

14. The modeling and simulation infrastructure within DOD needs to be improved. This is a major challenge since the necessary infrastructure is not well developed. Individual discipline-oriented simulation tools exist but most are embedded in specialized organizations. Data communication standards and tools do not exist to exploit the broad range of tools required in weapon system and manufacturing process design. Interoperability of models and simulations across services is not well developed.

15. If distributed interactive simulation is used to make acquisition decisions, the elements of the simulation network need to provide an environment sufficiently accurate so results can be used with confidence. Participating weapons systems need to reflect accurately system capabilities and characteristics in a realistic and accurate synthetic environment. Verification, validation and accreditation is required of both weapon systems and synthetic environments.

16. Knowledge gained by using virtual prototypes will enhance the fundamental understanding of systems, subsystems and manufacturing processes and make it easier to optimize designs for performance, producibility and reliability.

17. The risks of simulation should not be overlooked. Designers of virtual prototypes must understand the critical assumptions contained in simulations. They can either accept validated programs or they must check the results in sufficient depth to ensure that the programmer did not make dangerous assumptions or omit critical factors and that the programmer reflects fully the subtleties of the designer's unique problems.

RECOMMENDATIONS

Acquisition Policy

1. Virtual prototypes should be utilized in lieu of physical prototypes whenever possible, and dual-use funding should be tar-

geted in this area to increase industrial flexibility.

2. Virtual reality has great potential, but it is not clear when DOD will benefit from this technology. Virtual reality research should be continued to facilitate its incorporation once it matures.

3. An organization needs to be established that is formally assigned the responsibility for establishing standards and common tools for verification, validation and accreditation of all synthetic environments.

4. Rapid prototyping tools and techniques greatly accelerate the development of a new product and should be required in contracts for parts and subsystems wherever possible. The use of stereolithography and similar technologies should be encouraged.

5. Software development tools that support the rapid construction of battlefield simulations need to be developed. Battlefield simulations must look real and must present the same conditions to all participants. The environments must provide semiautomated forces which mimic human behavior. Finally, models of realistic human performance and decision making need to be validated.

6. Virtual prototypes should be incorporated in developmental and operational test plans as a substitute for physical prototypes whenever possible and used to aid in the design of the tests performed during each phase of an acquisition. A virtual prototype can provide the test community with the ability to optimize the number of tests that are to be conducted as well as reduce the time required to collect the required data. Testers can conduct numerous iterations of the same test scenario to assist in the design of the tests that are to be performed during each phase of the acquisition process. Wherever possible a virtual prototype should be substituted for a physical prototype for destructive testing and fatigue analysis. For most developments virtual prototypes should be used in lieu of physical prototypes in acquisition phases prior to engineering and manufacturing development.

7. Establish a modeling and simulation infrastructure responsible for data communication standards and tools which do not exist today.

8. Validate and verify the emerging DIS environment to ensure it is accurate enough so simulation results can be used with confidence to support acquisition and training decisions.

Program Managers

1. Virtual prototypes are a powerful tool for managing program risk. Virtual prototypes should be used wherever possible to measure performance against milestone decision criteria. They can be used to test the system or high-risk subsystems against simulated threats, assess the effectiveness of the technology and also to evaluate the feasibility of the design for producibility.

2. Make virtual prototyping the central element in the approach to development and production. Require a virtual prototype in the concept evaluation phase and enhance its fidelity throughout the development and production process. Utilize the virtual prototype to achieve the "seamless transition" that reduces schedule and start-up costs.

3. Educate the functional matrix team members on the benefits realized from using a virtual prototype and, whenever possible, reduce or eliminate interim paper reports and replace them with access to the digitized database that supports the virtual prototype. Maximize the use of simulations with the virtual prototype to satisfy engineering, manufacturing, testing and logistical requirements, wherever possible.

4. Convert your drawing approval and configuration management procedures to a process that is digital and utilizes the evaluation of the virtual prototype as the mechanism through which these tasks are accomplished. Two-dimensional paper drawings should be replaced by three-dimensional digital designs that can be used to assemble the product electronically. Simulation can then be added to validate maintenance procedures and human factors.

5. Virtual prototypes are useful in obtaining and maintaining system support. They can positively influence product support at all levels of the acquisition process. Use virtual prototypes to demonstrate the "value-added" capabilities of your system while at the same time convincing the audience that the technical and financial risks associated with obtaining this capability are reasonable. Increase user involvement in the development process by providing a better foundation for user and developer communications.

6. Virtual prototypes will permit testing systems in a simulated battlefield at a very early stage in the development and thus allow optimizing the design for maximum "value-added" warfighting capability.

7. Virtual prototyping capabilities maximize the potential for dual-use products and processes and, as such, program managers should seek additional funding from the DOD dual-use program.

Industry

1. Virtual prototyping provides a clear, competitive edge to companies who embrace and successfully implement it. Encourage and support its use at every opportunity.

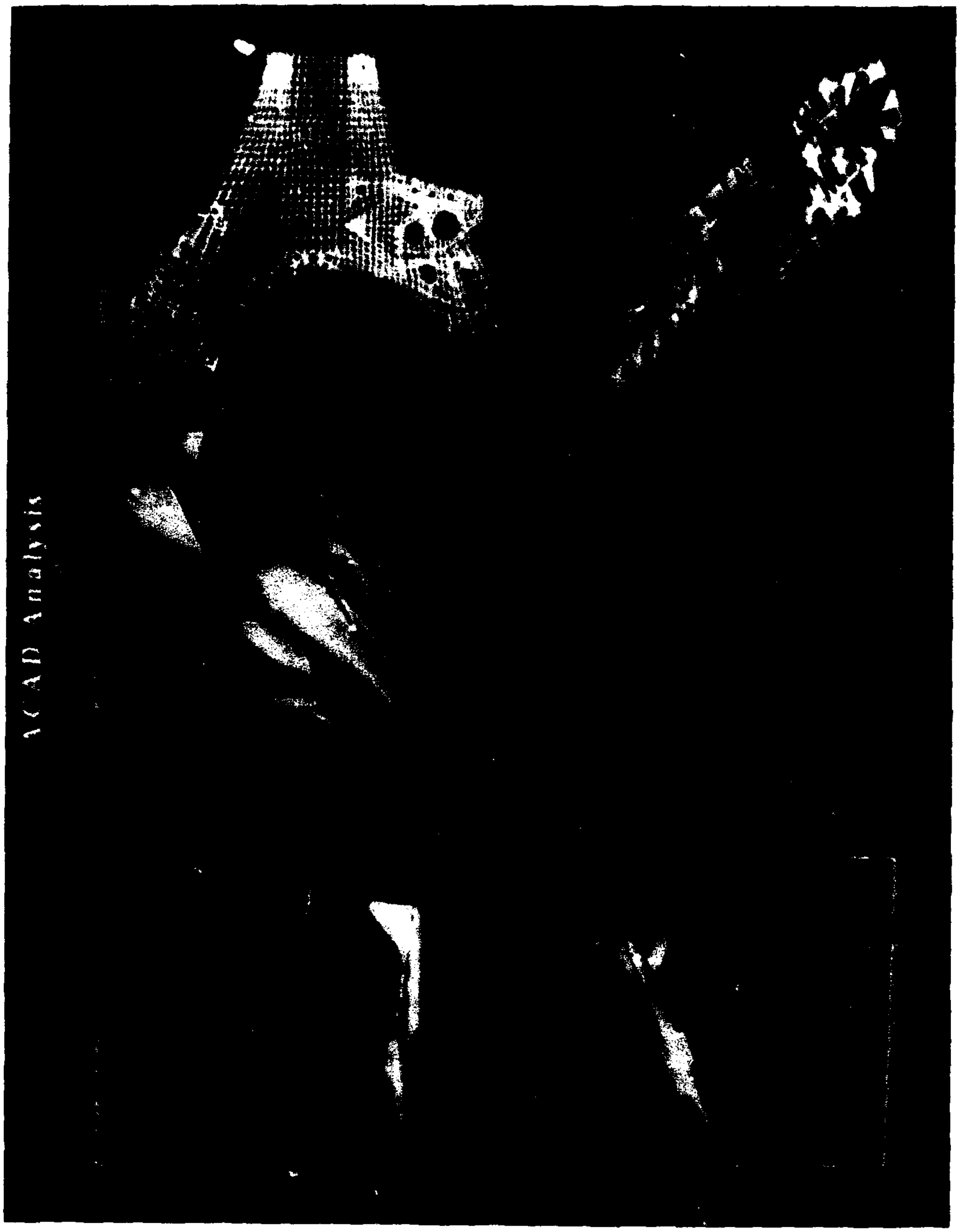
2. Concurrent engineering is an absolute requirement for competitiveness in the 1990s. Virtual prototyping will facilitate the adoption of this concept.

3. Develop the virtual prototype as early as possible and use it in internal and external marketing efforts. Make the virtual prototype database the vehicle for facilitating functional communications and the basis from which a "seamless" product development and production process can be implemented.

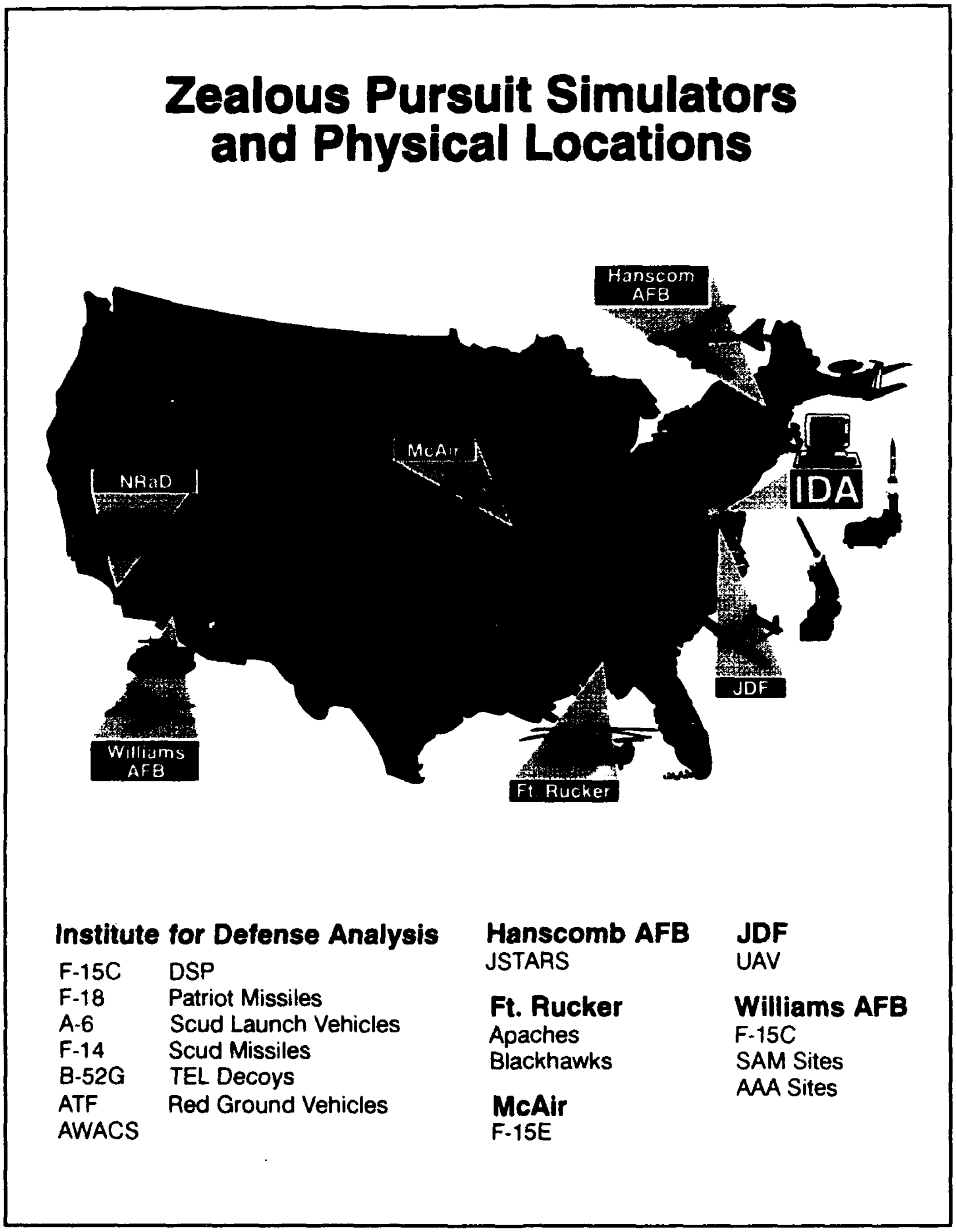
4. Senior management support is required in order to successfully implement the use of virtual prototyping. The conversion to digital design concepts will involve a major cultural change and a significant transition period should be allowed before mandatory conversion.

Color Plate 1. **Advanced Computer-Aided Design (Examples)**

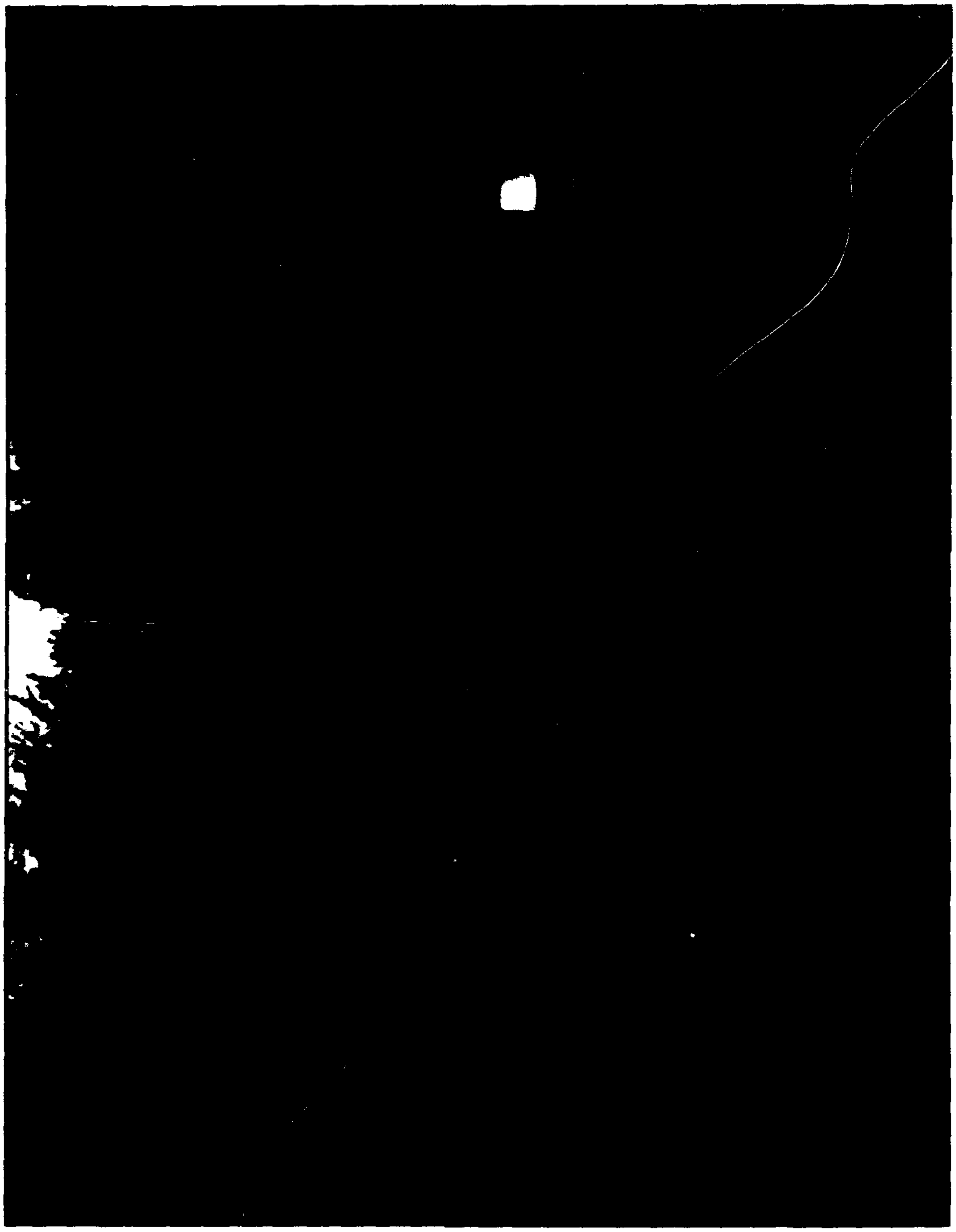
Color Plate 2. Examples of Meshing Techniques



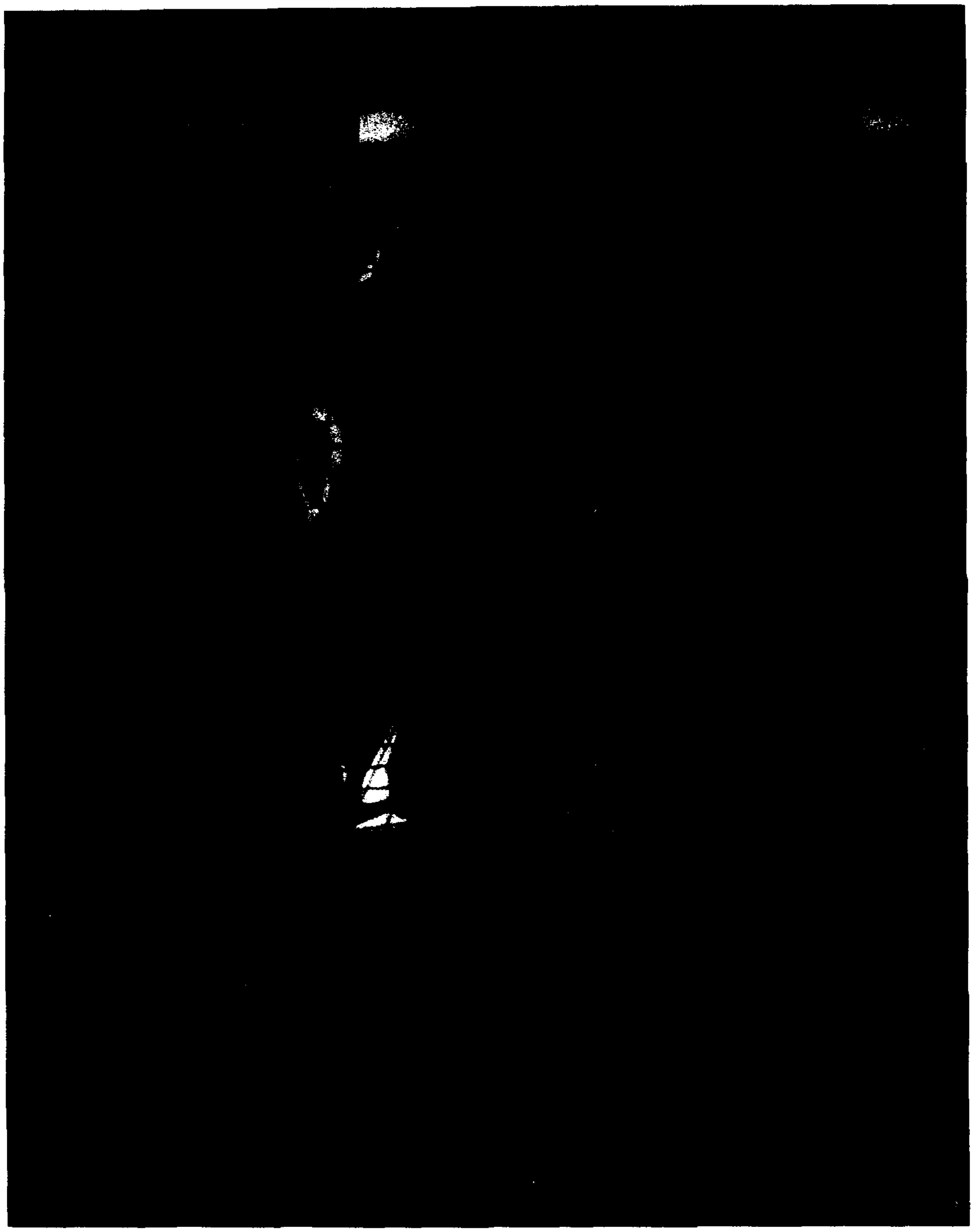
Color Plate 3. **Finite Element Analysis (Example)**



Color Plate 4. Zealous Pursuit Exercise



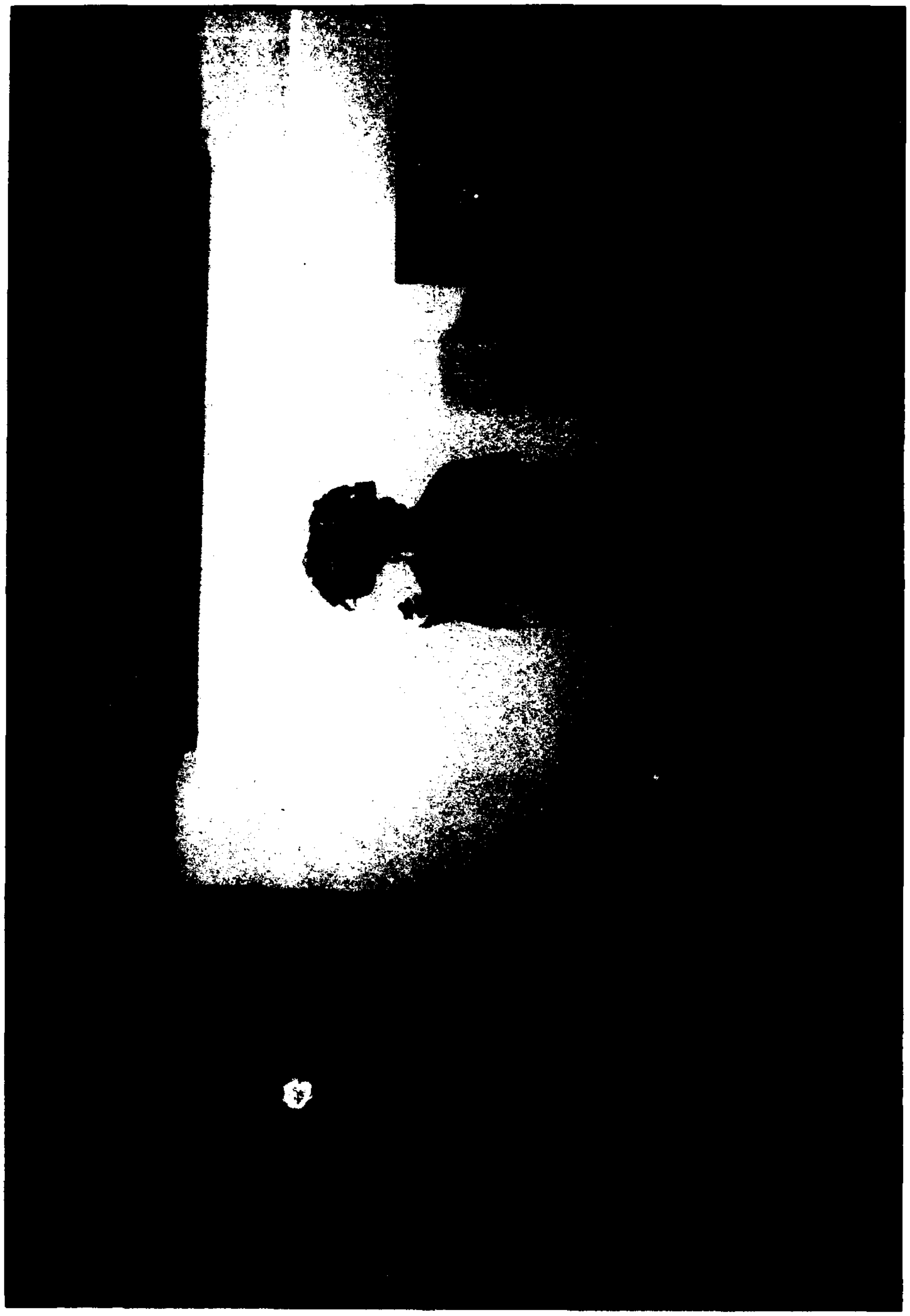
Color Plate 5. Comanche Helicopter



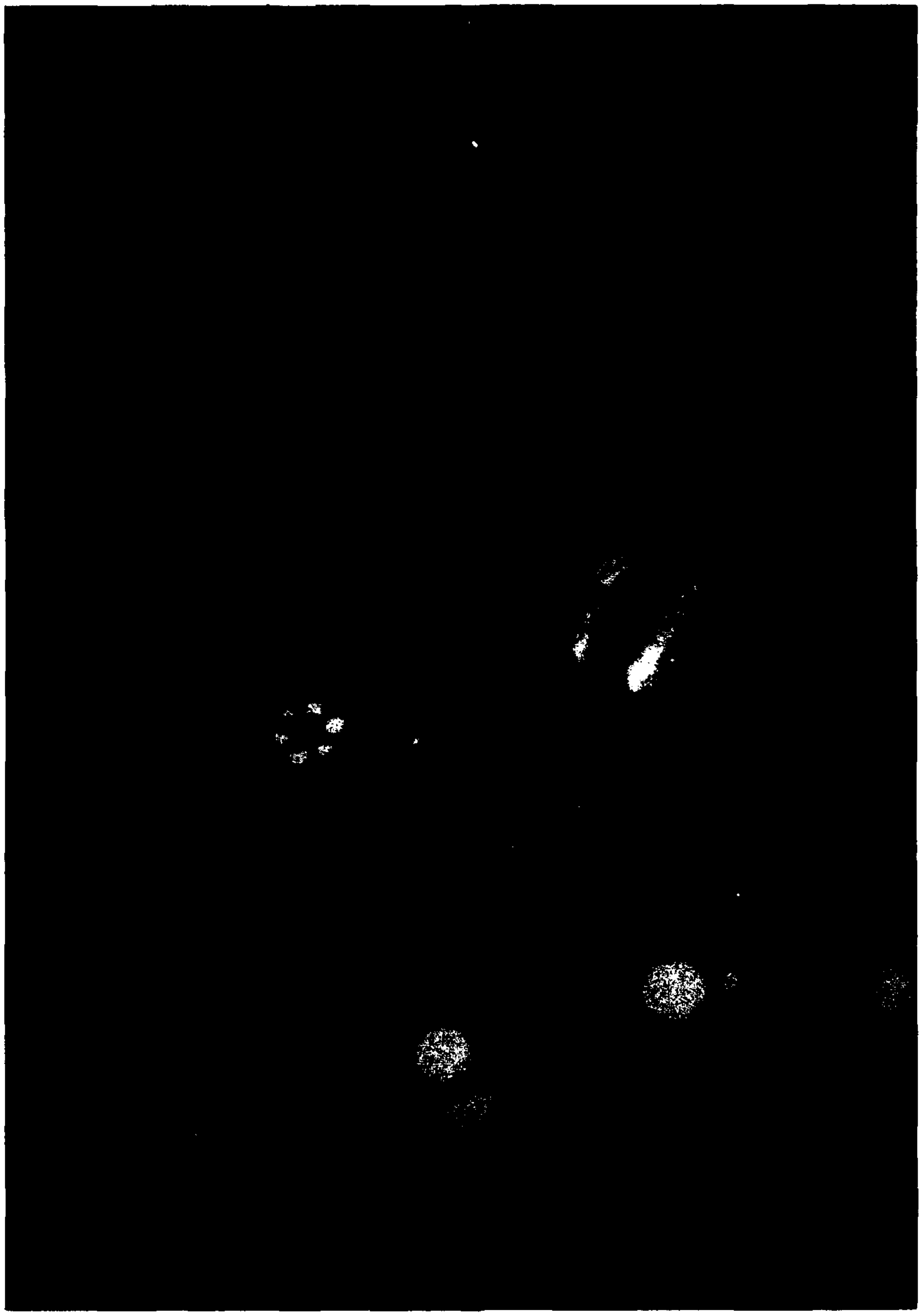
Color Plate 6. **Computer Analysis of Engine Parts**

Color Plate 7. Dual Cockpit Simulation with Head-Mounted Display

Color Plate 8. Reconfigurable Multifunction Displays in Cockpit



Color Plate 9. Virtual Kitchen



Color Plate 10. Virtual Molecule Docking

Appendix A

INTERVIEW QUESTIONNAIRE

Part I: Background Information

1. Organization:
2. Address:
3. Date of interview:
4. Name:
5. Duty title:
6. Phone number:
7. Type of organization?
   a. Government research activity
   b. Government purchasing organization
   c. University
   d. Design and manufacturing company
   e. Software organization
   f. Other
8. What best describes your position?
   a. Marketing
   b. Product design
   c. Software
   d. Manufacturing Engineer
   e. Research
   f. Other
9. How many years have you been with your organization?
   a. Less than 5
   b. 5 - 10
   c. More than 10

Part II: Familiarity with Virtual Prototyping

A virtual prototype is a computer-based simulation of a system or subsystem with a degree of functional realism that is comparable to a physical prototype. Virtual prototyping must facilitate immersion and navigation. A virtual prototype may be used in lieu of a physical prototype for product design, test and/or evaluation of specific characteristics of a candidate design.

The following questions pertain to your experience and your organization:

1. Are you familiar with the concept of virtual prototyping as I just described it?

2. Please indicate the extent your organization is using virtual prototyping on overall sys tems and on the specified subsystems:

	Not At All	Some	A Great Deal
a. Entire system	N	S	AGD
b. Subsystems	N	S	AGD
(1) Structures (fuselage, tank body)	N	S	AGD
(2) Mechanical (power plant, gears)	N	S	AGD
(3) Electrical (motors, batteries, power lines)	N	S	AGD
(4) Electronic (displays, computers, fire control)	N	S	AGD
(5) Chemical (composites, paints)	N	S	AGD

3. **How would you characterize manufacturing at your company?**

   a. Capital intensive

   b. Labor intensive

   c. Don't know

   d. Does not apply

If not involved in virtual prototyping, STOP HERE.

4. In your opinion what are the most significant advantages and disadvantages of virtual prototyping?

5. For what purpose are you using virtual prototyping?

6. What is the primary reason why your organization is involved with virtual prototyping?

   a. Competition

   b. Cost reduction

   c. Reduce design time

   d. Other

   e. Not involved

7. Listed below are several statements related to virtual prototyping. Please indicate if you agree (A), disagree (D), or don't know (DK) regarding each statement.

	Agree	Disagree	Don't Know
a. Virtual prototyping reduces design costs.	A	D	DK
b. Virtual prototyping reduces design time.	A	D	DK
c. Virtual prototyping produces more robust designs.	A	D	DK
d. Virtual prototyping makes it easier to transition from design to production.	A	D	DK
e. Virtual prototyping makes it easier to test prototypes.	A	D	DK
f. The defense industry is lagging the commercial sector in the utilization of virtual prototyping.	A	D	DK
g. U.S. industry is behind foreign firms in the use of virtual prototypes.	A	D	DK
h. Virtual prototyping makes it easier to create a model of a new product.	A	D	DK

	Agree	Disagree	Don't Know
i. Virtual prototyping facilitates customer feedback.	A	D	DK

8. To your knowledge, who else is using virtual prototyping in your organization?

9. How significant are the following factors in the use of virtual prototypes on systems and subsystems?

	Not Significant	Significant	Don't Know
a. Suitability of system/subsystem to virtual prototyping.	S	NS	DK
b. Software expertise in your organization.	S	NS	DK
c. Commitment of top management.	S	NS	DK
d. Competition.	S	NS	DK
e. Organizational support.	S	NS	DK

10. Do you think that virtual prototyping will replace physical prototypes in the future for systems and the following specified subsystems?

	No	Somewhat	A Great Deal	Don't Know
a. Entire system	N	S	AGD	DK
b. Subsystems:				
(1) Structures	N	S	AGD	DK
(2) Mechanical	N	S	AGD	DK
(3) Electrical	N	S	AGD	DK
(4) Electronic	N	S	AGD	DK
(5) Chemical	N	S	AGD	DK

11. The following statement refers to the validation of a virtual prototype. Validation is the process of determining (a) the manner and degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model and (b) the confidence that should be placed on this assessment. How much confidence do you have that virtual prototypes are an accurate representation of the real world for entire systems and the specified subsystems?

	None	Somewhat	A Great Deal	Don't Know
a. Overall system	N	S	AGD	DK
b. Subsystems:				
(1) Structures	N	S	AGD	DK
(2) Mechanical	N	S	AGD	DK
(3) Electrical	N	S	AGD	DK
(4) Electronic	N	S	AGD	DK
(5) Chemical	N	S	AGD	DK

Part III: DOD Policy Implications

The questions in Part III apply to DOD contractors only. If you are not a DOD contractor, please skip to Part IV.

1. In your opinion, does current DOD policy have any impact on your decision to use virtual prototypes?

   a. Yes, a significant impact.

   b. Yes, some impact.

   c. No.

   d. Don't know.

2. Should DOD modify its current acquisition policy to encourage the use of virtual prototyping? If yes, what changes do you recommend?

3. Should DOD modify its current DODD 5000.1 and DODI 5000.2 milestone decision process based on the impact of virtual prototyping? If yes, what changes do you recommend?

4. Listed below are several statements relating to virtual prototypes (VP) on defense systems and subsystems. For each of these statements please indicate whether you Agree (A), Disagree (D) or Don't Know (DK).

	Agree	Disagree	Don't Know
a. VP will replace physical prototypes for entire systems by the year 2000.	A	D	DK
b. VP will replace physical prototypes for the following subsystems by the year 2000:			
(1) Structures	A	D	DK
(2) Mechanical	A	D	DK
(3) Electrical	A	D	DK
(4) Electronic	A	D	DK
(5) Chemical	A	D	DK

Part IV: Application of Virtual Prototyping

1. Please identify the systems/subsystems on which you have used virtual prototyping.
2. What has been your experience with virtual prototyping?
3. What is your assessment of the future of virtual prototyping at your company and in your industry?

Appendix B
INTERVIEWS AND PERSONAL CONTACTS

Dr. George P. Abrahamson
Chief Scientist of the Air Force
The Pentagon, Room 4E320
Washington, DC 20301

Mr. Nick Ali
Program Manager CCTT
International Business Machines Corporation
3051 Technology Parkway, Suite 100
Orlando, FL 23826

Lt Col Philip Amburn, USAF
Instructor of Computer Science
Air Force Institute of Technology
Wright-Patterson AFB, OH 45433-6583

Mr. Michael R. Anderberg
Office of the Assistant Secretary of Defense
Programs, Analysis and Evaluation (Resource Analysis)
The Pentagon, Room 2D278
Washington, DC 20301

Mrs. Joan E. Bebb
Chief Engineer
TRW Systems Engineering and Development Division
18901 South Wilmington Avenue
Carson, CA 90746

Mr. Hancel Beckworth
Principle Systems Analyst
Eagle Technology/Logicon
10560 Arrowhead Drive
Fairfax, VA 22030

Mr. Michael A. Biferno
Senior Engineer/Scien[illegible]
McDonnell Douglas Transport Aircraft
Internal Mail Code 78-73
3855 Lakewood Blvd.
Long Beach, CA 90846

Major Joseph E. Bond, USAF
Defense Modeling and Simulation Office
1901 N. Beauregard Street, Suite 504
Alexandria, VA 22311

Dr. William Bricken
Principle Scientist
Human Interface Technology Laboratory
Washington Technology Center
University of Washington
Seattle, WA 98195

Dr. Harold K. Brown
Associate Professor of Electrical and Computer Engineering
Florida Institute of Technology
150 West University Blvd.
Melbourne, FL 32901-6988

BG (P) William H. Campbell, USA
Program Executive Officer, Command and Control
Fort Monmouth, NJ 07033

Mr. Wendell Chun
Robotic Systems, Civil Space and Communications
Martin Marietta
P.O. Box 179
Denver, CO 80201

Dr. Earl J. Craighill
Program Manager, Network Information System
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

Mr. Rich Crispo
Manager, Engineering Computing
The Boeing Company
Boeing Defense and Space Group
P.O. Box 3999, MS 87-84
Seattle, WA 98124-2499

Mr. Benjamin E. Cummings
U.S. Army Research Laboratory
ATTN: AMSRL-CI-S
Aberdeen Proving Ground, MD 21005-5066

Mr. Michael J. Daily
Senior Member of the Technical Staff
Hughes Perception Systems
Research Laboratories, MS 9L96
3011 Malibu Canyon Road
Malibu, CA 90265-4799

Mr. Michael Dominguez
Office of the Assistant Secretary of Defense
Programs, Analysis and Evaluation (Resource Analysis)
The Pentagon, Room 3E836
Washington, DC 20301

Brig Gen Robert W. Drewes, USAF
Director, Contracting and Manufacturing Policy
Office of the Secretary of the Air Force
ATTN: SAF/AQC
The Pentagon, Room 4C261
Washington, DC 20301

Mr. David S. Eccles
Director, Computer-Aided Engineering Dept.
The Aerospace Corporation
2350 E. El Segundo
El Segundo, CA 90245-4691

Mr. Robert (Dick) Eddy
General Dynamics, Electric Boat Division
75 Eastern Point Road, Mail Stop C62-3
Groton, CT 06340-4989

Dr. Robert Eggleston
Armstrong Laboratory
ATTN: WL/CFHP
Wright-Patterson AFB, OH 45433-6573

Mr. Ronald D. Eicher
Senior Group Leader
Martin Marietta Denver Aerospace
P.O. Box 179
Denver, CO 80201

Dr. Eugene S. Ferguson
Professor of History Emeritus
University of Delaware
54 Winslow Road
Newark, DE 19711

Mr. Michael J. Ferranti
Flight Simulation Facility Supervisor
Sikorsky Aircraft
Mail Stop S325A
6900 Main Street
Stratford, CT 06601-1381

Mr. Kurt D. Fickie
U.S. Army Research Laboratory
ATTN: AMSRL-CI-S
Aberdeen Proving Ground, MD 21005-5066

Mr. Brian C. Fleming
Manager, Scientific Applications Group
CAD-PRO Systems, Inc.
8101 E. Prentice, Suite 300
Englewood, CO 80111

Dr. Thomas A. Furness III
Director
Human Interface Technology Laboratory
Washington Technology Center
University of Washington, FJ-15
Seattle, WA 98195

Dr. Jacques S. Gansler
Senior Vice President
The Analytic Sciences Corporation (TASC)
1101 Wilson Blvd., Suite 1500
Arlington, VA 22209

Mr. Todd R. Gerhardt
Manager, Advanced Engineering Systems
Kohler Company
444 Highland Drive
Kohler, WI 53044

Mr. Brian F. Goldiez
Director, Research and Development
Institute for Simulation and Training
University of Central Florida
12424 Research Parkway, Suite 300
Orlando, FL 32826

Mr. Terrence D. Gossett
Chief, Simulation & Aircraft Systems Division
Ames Research Center M.S. 243-4
Moffett Field, CA 94035-1000

Mr. Dick Hartke
Aerospace Industries Assoc. of America
National Center for Advanced Technology
1250 Eye Street NW
Washington, DC 20005

BG Edward Hirsch, USA (Ret.)
Provost and Deputy Commandant
Defense Systems Management College
Fort Belvoir, VA 22060-5565

Dr. Ronald C. Hofer
Technical Director
Simulation, Training and Instrumentation Command
12350 Research Parkway
Orlando, FL 32826-3276

Mr. Stephen B. Holdener
Customer Relations
The Boeing Company
Boeing Defense and Space Group
P.O. Box 3999, MS 85-11
Seattle, WA 98124-2499

Ms. Linda A. Houseman
Research Associate
University of North Carolina
Box 3175 Sitterson Hall
Chapel Hill, NC 27599-3175

Mr. Richard D. James
Manager, Research & Engineering Programs
The Boeing Company
Boeing Defense and Space Group
1700 North Moore Street, 20th Floor
Rosslyn, VA 22209-1989

Mr. Jim Kagdis
Director of Marketing
Boeing-Sikorsky
JPO Commanche
Trumbull, CT 06611

Mr. David L. Kellogg
Engineering Staff Specialist
General Dynamics
P.O. Box 478
Fort Worth, TX 76101

LTC David E. Kendrick, USA
Office of the Secretary of the Army
Research, Development and Acquisition
The Pentagon, Room 3E411
Washington, DC 20301

Mr. Jim Koenig
Senior Engineer/Scientist
Douglas Aircraft Company
Internal Mail Code 78-73
3855 Lakewood Blvd.
Long Beach, CA 90846

Dr. Walter B. LaBerge
Holder, Acquisition Policy Chair
Defense Systems Management College
Fort Belvoir, VA 22060-5565

Dr. Hng T. Le
Systems Engineer
International Business Machines Corporation
9500 Godwin Drive
Manassas, VA 22110

Ms. Evelyn Lemon
Systems Manager, Information Systems
Port of Seattle, Pier 66
P.O. Box 1209
Seattle, WA 98111

Dr. Allan J. Lightman
Research Physicist
University of Dayton
Research Institute KL-462
300 College Park
Dayton, OH 45469-0140

Mr. James A. Mains
Manager, Engineering Visualization
TRW Engineering and Test Division
One Space Park
Redondo Beach, CA 90278

Dr. William S. Mark
Chief Scientist
Lockheed Missiles and Space Company, Inc.
Org 96-01, Bldg 254E
3251 Hanover Street
Palo Alto, CA 94304-1191

Mr. Charles E. Massey
Systems Engineering Manager
International Business Machines Corporation
9500 Godwin Drive
Manassas, VA 22110

Mr. Grant McMillian
Chief, Performance Assessment and Interface Technology
Armstrong Laboratory
ATTN: WL/CFHP
Wright-Patterson AFB, OH 45433-6573

Dr. Peter M. Meenan
Manager, Computer Graphics and Systems Program
General Electric Company
Bldg. KW, Room C217
P.O. Box 8
Schenectady, NY 12301

Mr. W. M. (Max) Mercer
Manager, Combat Systems Trainer Engineering
International Business Machines Corporation
9500 Godwin Drive
Manassas, VA 22110

Lieutenant Colonel Erik G. Mettala, USA
Defense Advanced Research Projects Agency (SISTO)
Virginia Square Station
3701 N. Fairfax Drive
Arlington, VA 22203-1714

Mr. Richard Moore
Director of Process Engineering
TRW Systems Engineering & Development Division
1800 Glenn Curtis Drive
P.O. Box 6213
Carson, CA 90749-6213

Dr. J. Michael Moshell
Associate Professor of Computer Science
Institute for Simulation and Training
University of Central Florida
12424 Research Parkway, Suite 300
Orlando, FL 32816

Dr. Donald L. Nielson
Vice President, Computing and Engineering
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

Mr. Cecil Patterson
Director Information Systems
Port of Seattle, Pier 66
P.O. Box 1209
Seattle, WA 98111

Mr. Joseph Rhyu
3D CAM Corporation
21000 Osborne Street, Suite 4
Kenova Park, CA 91304

Mr. Steve Rice
Senior Engineer/Scientist
McDonnell Douglas Transport Aircraft
Internal Mail Code 78-73
3855 Lakewood Blvd.
Long Beach, CA 90846

Dr. Dana B. Rogers
Professor
University of Dayton
Electrical Engineering Department
300 College Park
Dayton, OH 45469-0150

Captain Timothy F. Rohaly, USA
U.S. Army Research Laboratory
ATTN: AMSRL-CI-S
Aberdeen Proving Ground, MD 21005-5066

Mr. Walker Royce
Project Manager
TRW Systems Engineering & Development Division
1800 Glenn Curtis Drive
P.O. Box 6213
Carson, CA 90749-6213

Mr. Dennia W. Ruhl
Senior Engineer
International Business Machines Corporation
Dept. 41HC M/S 630
Neighborhood Road
Kingston, NY 12401

Mr. Greg Saunders
Deputy Director
OASD (Production and Logistics)PR/MM
The Pentagon, Room 3B253
Washington, DC 20301

Dr. William J. Schroeder
Computational Scientist
General Electric Company
Bldg. KW, Room C211
P.O. Box 8
Schenectady, NY 123[illegible]

Dr. Wade H. Shaw Jr.
Professor
Florida Institute of Technology
150 West University Boulevard
Melbourne, FL 32901-6988

Mr. R. Kenneth Sigmund
Federal Sector Marketing
International Business Machines Corporation
6705 Rockledge Drive
Rockville, MD 20817

Mr. Ernie Smart
Advanced Applications Manager
Institute for Simulation and Training
University for Central Florida
12424 Research Parkway, Suite 300
Orlando, FL 32826

Dr. John R. Spofford
Research Scientist Robotics Section
Martin Marietta Space Systems
P.O. Box 179
Denver, CO 80201

Mr. Ram Sriram
Group Leader, Artificial Intelligence Center
Lockheed Missiles and Space Company, Inc.
Org 96-20, Bldg 254
3251 Hanover Street
Palo Alto, CA 94304-1191

Mr. Dennis D. Stafford
Division Head
University of Dayton
Electrical and Computer Engineering Division
300 College Park
Dayton, OH 45469-0150

Mr. Mike Sutten
Manager, Business Development
General Electric Company
ATL Building
Moorestown Corporate Center
Moorestown, NJ 08057

Mr. Gregory D. Swedberg
Section Manager, CAE Dept.
The Aerospace Corp.
2350 E. El Segundo Blvd.
El Segundo, CA 90245-4691

Mr. David F. Teti
Division Inc.
400 Seaport Court, Suite 101
Redwood City, CA 94063

Mr. Edwin A. Trier
Deputy Project Manager CATT
Simulation, Training and
Instrumentation Command
ATTN: AMCPM-CATT
12350 Research Parkway
Orlando, FL 32826-3276

Dr. David Y. Tseng
Laboratory Manager
Hughes Artificial Intelligence Center
Research Laboratories, Loc. MA, Bldg 25
3011 Malibu Canyon Road
Malibu, CA 90265-4799

Dr. Bernard J. Ulozas
Training Specialist
United States Navy
Instructional Technology Division (Code 152)
Navy Personnel Research and
Development Center
San Deigo, CA 92152-6800

Mr. Gary Vassighi
President
3D CAM Corporation
21000 Osborne, Suite 4
Canoga Park, CA 91304

Mr. Bruce Wright
Senior Technical Specialist, Avionics
Northrop Corporation
8900 E. Washington Blvd.
Pico Rivera, CA 90660-3765

...ohn S. Yuhas
... of the Secretary of the Army
Research, Development and Acquisition
The Pentagon, Room 3E479
Washington, DC 20301-0103

Appendix C

MODELING AND SIMULATION POINTS OF CONTACT

ARMY:
COL David Hardin, USA
U.S. Army M&S Management Office
1725 Jefferson Davis Highway, Suite 808
Arlington, VA 22202
703-607-3375 Office
703-607-3381 Fax

NAVY:
CAPT Tom L. Travis, USN
Office of the CNO
Modeling & Analysis Section (N812D)
2000 Navy Pentagon, Room 4A520
Washington, DC 20350-2000
703-697-3642 Office (DSN 227-3642)
703-693-9760 Fax (DSN 223-9760)

AIR FORCE:
Ms. Peggy Gordon
Air Force Modeling, Simulation & Analysis
Technical Support Division
624 9th Street NW, Suite 300
Washington, DC 2001-5303
202-504-5339, Ext. 101 Office
202-504-5352 Fax

MARINE CORPS:
COL John Kline, USMC
Marine Corps Modeling & Simulation Management Office
Training & Education Division
2006 Hawkins Drive
Quantico, VA 22134
703-640-2498 Office
703-640-2591 Fax

JOINT STAFF (J-7):
COL Lee McFann, USAF
Joint Chiefs of Staff, J-7
The Pentagon, Room 2B877
Washington, DC 20318-7000
703-697-1133 Office
703-693-7729 Fax

JOINT STAFF (J-8):
Mr. Bob Halayko
Joint Chiefs of Staff, J-8
Resources and Joint Programs Division
The Pentagon, Room 1D929
Washington, DC 20318-8000
703--693-4600 Office
703-693-4601 Fax

INTELLIGENCE:

Dr. Joe Durham
Director, Missile & Space Intelligence Center
Attn: MSC-3B
Redstone Arsenal, AL 35898
205-876-4934 Office
205-881-2537 Fax

DARPA:

COL Bob Reddy, USA
DARPA-DIRO
3701 N. Fairfax Drive
Arlington, VA 22203
703-696-2362 Office
703-696-2206 Fax

DEFENSE MODELING & SIMULATION OFFICE:

CAPT Bruce P. McClure, USA
Defense Modeling and Simulation Office
1901 N. Beauregard Street, Suite 504
Alexandria, VA 22131
703-998-0660 Office
703-998-0667 Fax

OSD (DT&E):

COL Charles B. Cook, USA
OSD, DT&E
The Pentagon, Room 3E1060
Washington, DC 20301
703-695-4608 Office
703-693-7030 Fax

OASD (PA&E):

Dr. Patricia Sanders
OASD, PA&E
The Pentagon, Room 2B256
Washington, DC 20301
703-697-3521 Office
703-693-5707 Fax

OSD (DDR&E):

Mr. Rick Menz
DDR&E, S&T/E&T
The Pentagon, Room 3D1089
Washington, DC 20301
703-695-0552 Office
703-695-4885 Fax

SDIO:

Mr. Stan Sheldon
SDIO
The Pentagon, Room 1E149
Washington, DC 20371
703-693-1594 Office
703-693-1700 Fax

OASD (C3I):

CDR Charlotte Gross, USN
OASD, C3I
1225 Jefferson Davis Highway, Suite 910
Arlington, VA 22202
703-746-7939 Office
703-746-7396 Fax

OASD (P&L):
Mr. John Walsh
OASD, FM&P (R&R/S&T)
The Pentagon, Room 3B930
Washington, DC 20301
703-695-1760 Office
703-693-7382 Fax

OASD (P&L):
Mr. Mike Zsak
OASD, P&L/WSIAD
The Pentagon, Room 2B322
Washington, DC 20301
703-756-8420 Office
703-756-0415 Fax

Appendix D

GLOSSARY OF SELECTED TERMS

3-D - Three-dimensional, refers to the visual display that exhibits breadth, height and thickness or depth. Standard 2-D computer images and television displays create a flat image with only height and breadth.

6 DOF - Six degrees of freedom, refers to the number of simultaneous directions or inputs a sensor can measure. Typically used to describe the combination of spacial positions (X, Y, Z) and orientation (roll, pitch, yaw).

Accreditation - An official determination that a model is acceptable for a specific purpose. Used synonymously with certification.

Augmented Reality - Use of transparent eyeglasses on which data can be projected. This allows a user to operate a system (fly an aircraft, drive a tank) while having needed data displayed in the direct line of vision.

CAD - Computer-aided design, a precision software drawing tool which speeds up the design process by automating the work.

Computer Models and Simulations - There are three broad classes as follows:

Computer Models - Systems and forces and their interaction are primarily represented in computer code. The models can differ greatly in the level of detail of the representation, and there may be some interaction with the model while it is running.

Manned Weapon System Simulations - Individual weapon systems are modeled (e.g., by a simulator) and typically are controlled by a human operator. Principal emphasis is on the situation where the individual simulations interact together through a distributed network. The archetype of this class is SIMNET.

Instrumented Tests and Exercise - Troops, weapon systems, and support systems interact in an environment as real as possible, with instrumentation being used to collect and distribute status data on the force elements. Activities at the National Training Center are a representative example.

Cybernetics - The study of human control functions and the mechanical and electronic systems designed to replace or emulate them, including computers. "Cyber," as a prefix, denotes anything related to computer environments, especially things that involve extensive interaction by the user.

Cyberspace - Any shared reality based computer connections. While virtual reality is a form of cyberspace, cyberspace is not a virtual reality. Also, a science-fiction term coined by William Gibson in his book *Neuromancer* to describe a virtual universe within a global computer network allegorical to the current telephone system, but providing a multisensory experience of "being there," not just an auditory experience.

DataGlove - A glove wired with sensors and connected to a computer system for gesture recognition. DataGlove is a trademark of VPL Research.

Environment - In virtual reality terms, this is a computer-generated model that can be experienced from the "inside" as if it were a place.

Force Feedback - An output device that transmits pressure, force or vibration to provide the virtual reality participant with the sense of touch. Force feedback simulates weight or resistance to motion.

Haptic - Refers to all the physical sensors that provide a sense of touch at the skin level and force feedback information from muscles and joints.

HMD (head-mounted display) - A set of goggles or a helmet, with small displays in front of each eye that generate images, seen by the wearer as being 3-dimensional.

Immersion - When one or more of a virtual reality participants senses (eyes or ears, generally) are isolated from the surrounding environments and only receive information coming from a computer-generated environment.

LCD - Liquid crystal display, used in products such as miniature televisions, portable computers and wristwatches.

LED - Light-emitting diode, a small semiconductor device that generates a point of light.

Model - A physical, mathematical or otherwise logical representation of a real-world system, entity, phenomenon or process.

Modeling and Simulation Interoperability - The ability of a model or simulation to provide services to, and accept services from, other models and simulations, and to use the services so exchanged to enable them to operate effectively together. See also modeling and simulation.

Joint modeling and simulation is the representations of joint and Service forces, capabilities, materials, services, and facilities used in the joint environment by two or more military services.

Common use modeling and simulation is the use of modeling and modeling applications, services, materials or facilities provided by a DOD component to two or more DOD components.

Multisensory I/O - The use of more than one sensory mechanism (visual, aural, tactile, etc.) to interact with a computer-generated environment. See virtual interface.

NTSC - National Television Standards Convention, the television standard used in the United States and other parts of the world. An interlaced signal provides two fields of information in a single frame, with a total of 525 lines of horizontal resolution, each 1/30th of a second

Occlusion - The vision effect of closer objects overlapping or occluding more distant ones, providing visual clues to judge how close objects are from the viewer. Slight head motions provide more information about occlusions.

Parallax - The vision effect of having two eyes viewing the same scene from slightly different positions which creates a sense of depth. Computer-generated environments, one for each eye, artificially create the parallax effect.

Pixel - A "picture element," refers to the smallest visual unit in an image on a computer display.

Polygon - A flat plane figure with multiple sides, the basic building block of virtual worlds. The more polygons a computer can display and manipulate per second, the more realistic the virtual world will appear. Humans perceive the equivalent of 80 million polygons at more than 30 frames per second in normal vision.

Real Time - The ability of a computer simulation to respond to inputs such that a human

perceives an instantaneous response, typically less than 50 milliseconds.

Reality Engine - Any computer system specifically designed to generate virtual reality worlds.

Rendering - The computer process of calculating and drawing computer images on a display device.

Shutter Glasses - Stereoscopic viewing eyeglasses that alternately reveal an image to the left and right eye to create the parallax effect giving a sense of depth (each eye receives a slightly different image). The shutters are typically composed of electrically switched LCD or Polaroid material and have no moving parts.

SIMNET - Simulation Network Project, a joint ARPA and U.S. Army research project concerning the use of distributed interactive simulation on local and wide area networks.

Simulation - A method for implementing a model over time. Also, a technique for testing, analysis or training in which real-world systems are used, or where real-world and conceptual systems are reproduced by a model. There are three classes of simulation:

> **Virtual Simulation** - Systems simulated physically and electronically. Examples include individual aircraft simulators and virtual prototypes.
>
> **Constructive Simulation** - Includes wargames, models and analytic tools.
>
> **Live Simulation** - Operations with real forces and real equipment. Examples include large scale live exercises such as REFORGER and exercises at locations such as the National Training Center.

Synthetic Battlefield - A specific application of a synthetic environment, consisting of simulations of the components of an actual battlefield (air, land and/or sea).

Synthetic Environment - Interconnected simulations that represent activities with a high level of realism ranging from simulations of theaters of war to factories and manufacturing processes. They are created by a confederation of computers, connected by local and wide area networks and augmented by super-realistic special effects and accurate behavioral models. They allow complete visualization of, and total immersion into, the environment being simulated. They represent the "real world" precisely.

Telepresence - The experience of being in another location, usually created by remotely located sensors (visual, aural, tactile) and possibly remote manipulator mechanisms.

Validation - The process of determining the manner and degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model and the confidence that should be placed on this assessment.

Verification - The process of determining that a model implementation accurately represents the developer's conceptual description and specifications. It consists of two basic parts:

> **Logical and mathematical verification** ensures that the basic equations, algorithms, etc., are as the designer intended.
>
> **Code verification** ensures that these representations have been correctly implemented in the computer program, including verifying that computations will not be erroneous by virtue of inappropriate numerical techniques or other implementation decisions.

Virtual - Refers to the essence or effect of something, not the fact.

Virtual Images - Visual, auditory and tactile stimuli that are transmitted to the sensory end organs so they appear to originate from within the three-dimensional space surrounding the user.

Virtual Interface - A system of transducers, signal processors, computer hardware and software that create an interactive medium through which information is transmitted to the senses in the form of three-dimensional virtual images. The psychomotor and physiological behavior of the user is monitored and used to manipulate the virtual images.

Virtual Prototype - A computer-based simulation of systems and subsystems with a degree of functional realism comparable to a physical prototype that facilitates immersion and navigation. Virtual prototypes are used for test and evaluation of specific characteristics of a candidate design.

Virtual Reality - The effect created by generating an environment that does not exist in the real world. Usually, a stereoscopic display and computer-generated three-dimensional environment giving the immersion effect. The environment is interactive, allowing the participant to look and navigate about the environment, enhancing the immersion effect. Virtual environment and virtual world are synonyms for virtual reality.

Visualization - The formation of an artificial image that cannot be seen otherwise. Typically, abstract data that would normally appear as text and numbers is graphically displayed as an image. The image can be animated to display time varying data.

Appendix E
BIBLIOGRAPHY

"A Review of Study Panel Recommendations for Defense Modeling and Simulation." IDA Document D-1161, (Alexandria, Va.: Institute for Defense Analysis, June 1992):A-14 - 22.

Arthur, Lowell Jay. "Quick & Dirty." *Computerworld* (14 December 1992).

Ashley, Steven. "Rapid Prototyping Systems." *Mechanical Engineering* (April 1991).

Association of the United States Army. *The Army Budget for Fiscal Years 1992 and 1993.* (Arlington, Va.: May 1991):37-38, 50-53.

Berry, F. Clifton Jr., "War Breaker: Level of Power." *National Defense* (December 1992):5-7.

Black, J. T., *The Design of the Factory with a Future* (New York City, N.Y.: McGraw-Hill, 1991).

Beckert, B. A., "Cutting It in Rapid Prototyping." *Computer-Aided Engineering* (September 1991).

Berry, F. Clifton Jr., "Re-Creating History: The Battle of 73 Easting." *National Defense* (November 1991).

Bricken, William. "A Vision of Virtual Reality." (Seattle, Wash.: HITL-P-90-1, University of Washington, July 1990)

— "Software Architecture for Virtual Reality." (Seattle, Wash.:HITL-P-90-4, University of Washington, July 1990)

— "Virtual Reality, Directions of Growth." (Seattle, Wash.: HITL-R-90-1, University of Washington, 10 September 1990)

Bylinsky, Gene. "The Marvels of 'Virtual Reality.'" *Fortune* (3 June 1991):138.

Carrabine, Laura. "Listening for E.T." *Computer-Aided Engineering* (September 1991).

"CATIA Data Management and CATIA Data Management Access" (International Business Machines Corporation, 1990).

"Changing an Army: An Oral History of General William E. DePuy, USA Retired" (Carlisle Barracks, Pa.: Army War College/Army Military History Institute, CMH 70-23).

Chaudhry, Anil. "From art to part." *Computerworld* (9 November 1992).

Chevalier, Peter W. "Group Technology: The Connecting Link to Integration of CAD and CAM." *Computer and Automated Systems Association of the Society of Mechanical Engineers* (September 1985):177.

Churbuck, David C. "Applied Reality." *Forbes* (14 September 1992):486.

"Comanche RAH-66." (Trumbull, Conn: Boeing Sikorsky Team, April 1992)

Cook, Brian M. "Rapid Prototyping: Designing a New Industrial Revolution." *Industry Week* (3 June 1991).

Cringely, Robert X. "Welcome to the Future." *Success* (September 1992):22.

Cruz-Neira, et al. "The CAVE: Audio Visual Experience Automatic Visual Environment." *Communications of the ACM* (Vol. 35, Iss. 6: June 1992):64-72.

Cutkosky, M., et al. "PACT: An Experiment in Integrating Concurrent Engineering Systems." *IEEE Computer Special Issue* (January 1993).

Defense Modeling and Simulation Office. "Defense Modeling and Simulation Initiative" (1 May 1992).

Department of Defense. *Annual Report to the President and the Congress* (January 1993).

Department of Defense. Director of Defense Research and Engineering. *Defense Science and Technology Strategy* (July 1992).

Department of Defense Directive 5000.1. "Defense Acquisition" *(23 February 1991).*

Department of Defense Instruction 5000.2. "Defense Acquisition Management Policies and Procedures "(23 February 1991).

Department of Defense Memorandum. "Memorandum of Agreement between the Vice Chairman of the Joint Chiefs of Staff and the Director for Defense Research and Engineering on Advanced Distributed Simulation Applications" (19 August 1992).

.Department of Defense Memorandum. The Deputy Assistant Secretary for Research and Technology. "Functional Requirements for the Army's Distributed Interactive Simulation (DIS) Network" (20 November 1992).

Department of Defense Memorandum. The Deputy Secretary of Defense. "DOD Modeling & Simulation Management Plan" (21 June 1991).

Department of the Army. *Army Science and Technology Master Plan, Vols. I and II* (November 1992).

Der, Sander S., et al. "A Multi-Sensor Digital Terrain Board for Processor Test and Evaluation." IRIS Symposium (17 March 1993).

"DOD's Manufacturing Technology" (ManTech Task Force, 18 December 1992).

Duan, W.; Zhou, J.; Lai, K. "FSMT: A Feature Solid-Modeling Tool for Feature-Based Design and Manufacture." *CAD* (January 1993).

Eisner, Robin. "Researchers See a Wealth of Applications for Virtual Reality." *The Scientist* (Vol. 5, No. 6, 18 March 1991):14-16.

"Final Assembly of 777 Nears." *Aviation Week & Space Technology* (12 October 1992):48.

Fisher, Scott S. "Virtual Interface Environment." (NASA/Ames Research Center, 1986)

Foston, Arthur L.; Smith, Carolena L.; Au, Tony. *Fundamentals of Computer-Integrated Manufacturing* (Englewood Cliffs, N.J.: Prentice Hall, 1991).

Fletcher, J. D. *A Review of Study Panel Recommendations for Defense Modeling and Simulation.* (Alexandria, Va.: Institute for Defense Analysis, Document D-1161, June 1992):10, 15, A-3, A-4, E-7.

Fritz, Mark. "The World of Virtual Reality." *Training* (February 1991):45.

Furness III, Thomas A. "An Introduction to Virtual Worlds Technology" (Seattle, Wash.: University of Washington, 1991).

— "Designing in Virtual Space" (Seattle, Wash.: HITL-R-87-1, University of Washington, 1991).

— "HIT Lab Overview of Projects" (Seattle, Wash.: HITL-P-91-1, University of Washington, 1991).

— "The Human Interface Technology Laboratory" (Seattle, Wash.: University of Washington, 1991).

— "The Super Cockpit Human Factors Challenges" (Seattle, Wash.: University of Washington, September, 1986).

Ferguson, Eugene S. *Engineering and the Mind's Eye* (Cambridge, Mass.: The MIT Press, 1992).

Gansler, Jacques S. "A Case for Dual-Use in Defense." *Washington Technology* (9 April 1991):15.

Ghosh, Pallab. "A Real Future for the Machine." *Management Today* (November 1991):120.

Gossett, Terry. "CSRF/AVTB Network Demonstrations" (Aeroflightdynamics Directorate, NASA/AMES Research Center, Calif.: 8-12 March 1993).

Hamilton, Joan O'C., et al. "Virtual Reality." *Business Week*, October 5, 1992.

"Head-Tracker Research." (University of North Carolina at Chapel Hill, August 1992):1.

Higgins, Robert C. *Analysis for Financial Management* (Homewood, Ill.: Richard D. Irwin, 1984):246.

"High-Tech Help for Low Vision." *NASA Tech Briefs* (Vol. 17, No. 2: February 1993):20.

"HIT Lab Overview and Projects 1991" (Seattle, Wash.: University of Washington, 1991).

Holbrook, Dave. "Stereo Viewing: Looking 'Into' Manufacturing." *Manufacturing Systems* (January 1991).

Hollmann, Martin. *Composite Aircraft Design* (Monterey, Calif.: Martin Hollmann Publishing, 1991).

Holloway, Richard L. *Art-Related Virtual Reality Applications at the University of North Carolina at Chapel Hill.* (Chapel Hill, N.C.: University of North Carolina, November 1990).

Horger, John D. "NVSIM: UNIX-based Thermal Imaging System Simulator." SPIE Symposium (14 April 1993).

Hudson, Neff. "Breakthrough Links Simulators with Live Action." *Army Times* (7 December 1992):32.

Hughes, David. "Sikorsky Exploits Workstations in RAH-66 CAD/CAM Design Work." *Aviation Week* (22 June 1992): 46-48.

Industry-University Cooperative Research Center for Simulation and Design Optimization of Mechanical Systems. "Program Review XI" (October 1992).

Jacobson, Robert. "Virtual Places: Strolling the Electronic Neighborhood" (Seattle, Wash.: HITL-M-89-4, University of Washington, August 1989).

— "Virtual Worlds, Inside and Out" (Seattle, Wash.: HITL-M-90-12, University of Washington, July 1990).

Jarett, Irwin M. *Financial Reporting Using Computer Graphics* (Somerset, N.J.: John Wiley & Sons, 1993).

Johnstone, Bob. "Seeing is Believing." *Far Eastern Economic Review* (16 January 1992):58.

Lane, Norman E. "Fidelity and Validity in Distributed Interactive Simulation: Questions and Answers." IDA Technical Note (Alexandria, Va.: Institute for Defense Analysis, September 1991).

Lang, Walter N. "A Mobile Electronic Battlefield." *National Defense* (November 1991).

Lucas, Eric. "Designing Airplanes: Boeing's 777th Heaven." *Hemispheres*, (March, 1993):69-70.

Mann, Robert W. "Scalpel! Clamp! Floppy Disk!" *Technology Review* (October 1991):66.

McDonald, Bruce. "Distributed Interactive Simulation - Operational Concept (Draft)" (University of Central Florida, February 1992).

McGee, Marianne K. "Emerging Technologies Offer New Competitive Opportunities." *Management Review* (March 1992).

Miller, Carmen. "Virtual Reality and Online Databases: Will 'Look and Feel' Literally Mean 'Look' and 'Feel'?" *Online* (Vol. 16, Nr. 6, November 1992):12-13.

— "Online Interviews Dr. Thomas A. Furness III, Virtual Reality Pioneer." *Online* (Vol. 16, No. 6, November 1992):14-27.

Norton, Robert L. *Design of Machinery* (New York City, N.Y.: McGraw-Hill, 1992).

Naylor, Sean D. "Tank Simulation Fails to Offer Real Answers." *Army Times* (8 March 1993):34.

Newquist, Harvey P. "Virtual Reality's Commercial Reality." *Computerworld* (30 March 1992):93.

O'Lone, Richard G. "Final Assembly of 777 Nears." *Aviation Week & Space Technology* (12 October 1992):48-50.

"PIXEL-PLANES 5 A Heterogeneous Multicomputer for Graphics" (University of North Carolina at Chapel Hill: July 1992).

Potts, Mark. "Virtual Reality." *The Washington Post* (16 August 1992):H-3.

— "Snaring Sharks in an Unreal World." *The Washington Post* (16 August 1992):H-1.

Prichett, Jack, editor. "Picturing Future Systems: TRW's Engineering Visualization Center." *Messages* (Winter 1992).

"Pro/Engineer" (Parametric Technology Corporation, 1992).

Puttre, Michael. "Virtual Reality Comes Into Focus." *Mechanical Engineering* (April 1991):56.

— "Virtual Prototypes Move Alongside Their Physical Counterparts." *Mechanical Engineering* (August 1992):59.

Rasmus, Daniel. "Working in a Virtual Factory." *Manufacturing Systems* (January 1990).

Rose, Frederick. "Boeing Names Woodard to Be Thornton Heir." *The Wall Street Journal* (12 March 1993).

Rheingold, Howard. *Virtual Reality* (New York City, NY: Simon & Schuster, 1991).

Reilly, Lucy. "ARPA Budget Has Dual-Use Focus." *Computerworld.*

Rudwick, Bernard H. *Systems Analysis for Effective Planning: Principles and Cases.* (New York, N.Y.: John Wiley & Sons, 1969):341-373.

Snoderly, John R. "How to Organize for Concurrent Engineering." *Program Manager, Journal of the Defense Systems Management College* (Vol. XXI, No. 4, DSMC 108: July-August 1992):2.

Taraman, Khalil, Editor. *CAD/CAM Integration and Innovation.* (Dearborn, Mich.: Society of Mechanical Engineers, 1985):177.

"The Human Interface Technology Laboratory." (Seattle, Wash: University of Washington, 1991):2,4.

Thorpe, Jack A. "Warfighting with SIMNET - A Report from the Front." *Proceedings: Interservice/Industry Training Systems Conference* (29 November 1992):264.

Trapp, Philip R. "Rapid Prototyping As an Alternative to the Pilot." *Modern Office Technology* (October 1991).

Turner, Richard; Hooper, Laurence, "IBM Ventures To Hollywood in Visual Effects." *The Wall Street Journal* (26 February 1993).

Ulerich, Phillip L. "Tips for Concurrent Engineering," *Machine Design* (20 August 1992).

U.S. Congress, Office of Technology Assessment. *Redesigning Defense: Planning the Transition to the Future U.S. Defense Industrial Base.* (Washington, D.C.: U.S. Government Printing Office, OTA-ISC-500, July 1991):11, 89-92.

U.S. Congress, Office of Technology Assessment. *Building Future Security.* (Washington, D.C.: U.S. Government Printing Office, OTA-ISC-530, June 1992):12, 51-75.

Varon, Elana. "ARPA High-Speed Networks to Revamp Navy Ship Design." *Federal Computer Week* (Vol. 7, No. 9, 26 April 1993):4.

"Virtual Prototypes Move Along Their Physical Prototypes." *Mechanical Engineering* (August 1992):59.

"Virtual Reality." *Business Week* (5 October 1992):97-104.

"Virtual Reality Comes into Focus." *Mechanical Engineering* (April 1992):2.

"War Breaker Simulation Phase One: The Zealous Pursuit Exercise." Defense Advanced Research Projects Agency (undated):2.

Wargo, James D. "Soldier-in-the-Loop Simulation for Improved Acquisition." DARPA briefing (31 July 1992).

Waters, Keith; Wang, Serkuang. "A 3-D Interactive Physically-Based Micro World." (Schlumberger Laboratory for Computer Science, 1990).

Wheeler, David L. "Computer-Created World of 'Virtual Reality' Opening New Vistas to Scientists." *The Chronicle of Higher Education* (13 March 1991):A6.

Wilder, Clinton, "Advanced Technology." *Computerworld* (27 April 1992).

— "Virtual Reality Seeks Practicality." *Computerworld* (27 April 1992):26.

Wilke, John R. "Parametric Faces Counterattack from Upended Rivals." *The Wall Street Journal* (11 March 1993).

Wohlers, Terry T. "CAD Meets Rapid Prototyping." *Computer-Aided Engineering* (April 1992).

— "Chrysler Compares Rapid Prototyping Systems." *Computer-Aided Engineering* (October 1992).

Zeid, Ibrahim. *CAD/CAM Theory and Practice* (New York City, NY: McGraw-Hill, 1991).

Appendix F

The following material is reprinted with permission of Professor Eugene S. Ferguson from his 1992 book, *Engineering and the Mind's Eye*. In the book, Professor Ferguson takes a probing look at the process of engineering design and argues that, despite modern technical advances, good engineering is still as much a matter of intuition and nonverbal thinking as of equations and computation.

Engineering and the Mind's Eye

Eugene S. Ferguson

Failures and Other Surprises

Engineering design is usually carried on in an atmosphere of optimistic enthusiasm, tempered by the recognition that every mistake or misjudgment must be rooted out before plans are turned over to the shops for fabrication.

Despite all the care exercised by individuals and all the systems that have been used to ensure that all the choices made in selecting parts and arranging them to work together will be correct, the evidence of faulty judgment shows up again and again in some of the most expensive and (at least on paper or on a computer screen) most carefully designed and tested machines of the twentieth century.

Of course there is nothing new about wrong choices and faulty judgments in engineering design. More than a hundred years ago, George Frost, editor of *Engineering News*, tried to track down the reasons for failures of bridges and buildings in order that civil engineers might learn from the mistakes of others. "We could easily," he wrote, "if we had the facilities, publish the most interesting, the most instructive and the most valued engineering journal in the world, by devoting it to only one particular class of facts, the records of failures. . . . For the whole science of engineering, properly so-called, has been built up from such records." [13]

A *Journal of Failures* such as that envisioned by Frost was never published; however, *Engineering News* and its successors have presented many valuable reports of engineering failures.[14] One of those reports—careful, comprehensive, knowledgeable, and fair to all parties—was published in *Engineering News* just a week after a cantilever railway bridge being built over the St. Lawrence River at Quebec City collapsed on August 29, 1907, killing 74 workmen.[15] (See Figures 7.1 & 7.2)

The writer of the report spent several days on and about the wreckage, piecing together the evidence before his eyes and the meager testimony of those who lived through the collapse. His conclusion, later confirmed by the Canadian government's year-long official inquiry, was that one of the compression members in the bottom chord of the landward ("anchor") arm of the cantilever truss buckled and immediately brought the rest of the span down on top of it. As figures 7.3 and 7.4 show, the bridge collapsed without significant movement to one side or the other. The failed

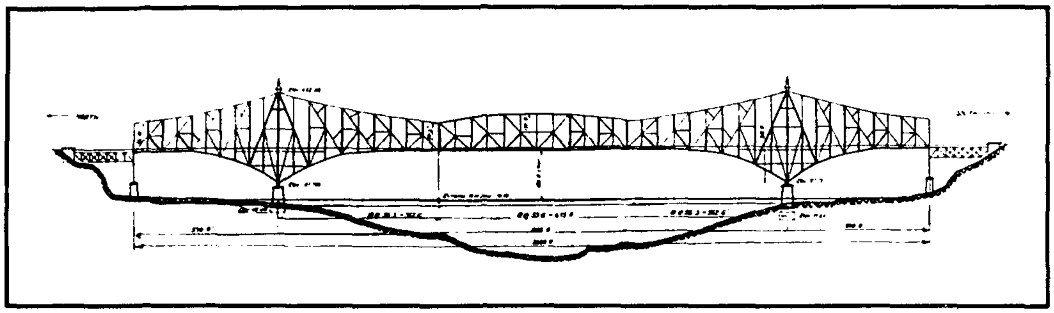


Figure 7.1. Drawing of steel cantilever railroad bridge being built across St. Lawrence River near Quebec City in 1907. (Phoenix Bridge Company Papers, Hagley Museum and Library)

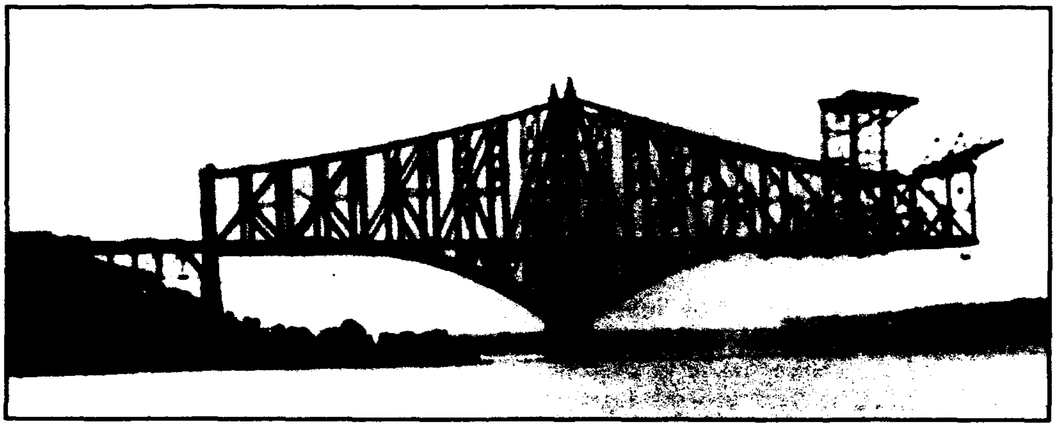


Figure 7.2. The southern end of the Quebec City bridge a few days before its collapse. (Phoenix Bridge Company Papers. I am indebted to Chris Baer for locating this photograph.)

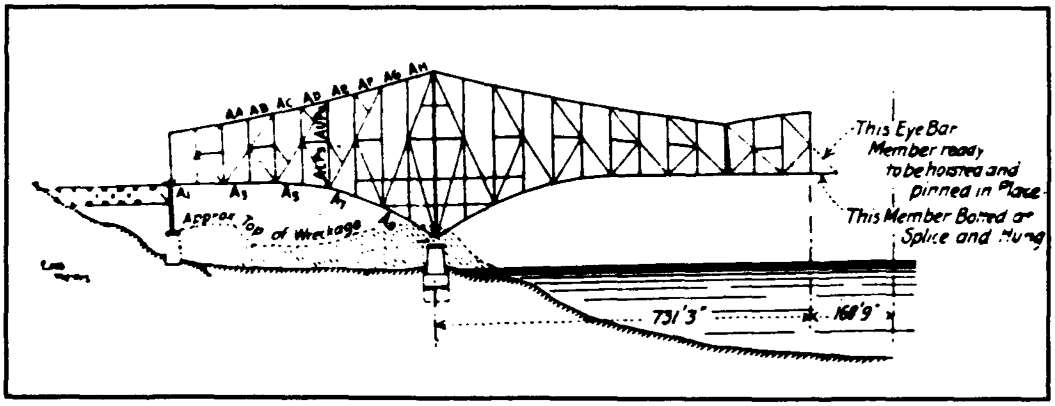


Figure 7.3. The Quebec City bridge fell straight down onto itself, leaving an amazingly compact line of wreckage (as indicated by "Approx. top of wreckage" in this drawing).

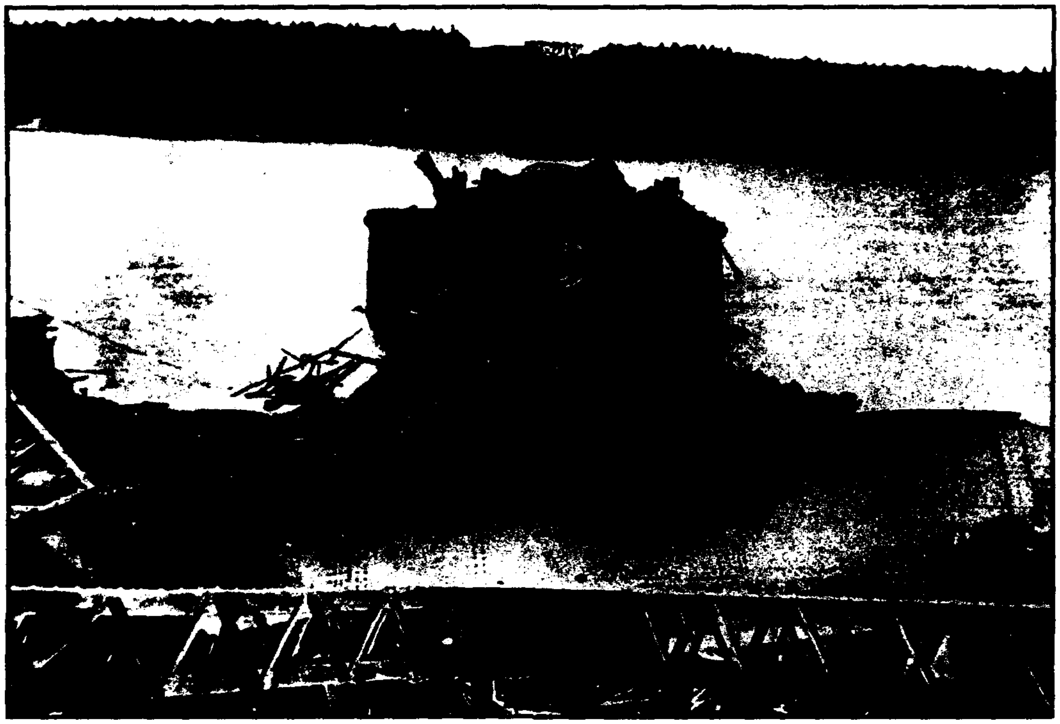


Figure 7.4. The low profile of the wreckage of the Quebec City Bridge is evident in this photograph. The pile of debris on the bridge pier was perhaps 10 feet above the pier's top surface. (Phoenix Bridge Company Papers, Hagley Museum and Library)

member, 57 feet long and $4\ ^1/_2$ feet deep, was of built-up construction, but in hindsight the bracing was not sufficient to prevent the whole member from buckling under lengthwise stress.

"Long and careful inspection of the wreckage," wrote the reporter, "shows that the material was of excellent quality; that the workmanship was remarkably good." But because the members were much larger than those used in ordinary bridges, he questioned the judgment that led to the design of the built-up compression members: "We step up from the ordinary columns of ordinary construction, tried out in multiplied practice, to enormous, heavy, thick-plated pillars of steel, and we apply the same rules. Have we the confirmation of experiment as a warranty? Except in the light of theory, these structures are virtually unknown. We know the material that goes into their make-up, but we do not know the composite, the structure." [16]

Within a few weeks after the Quebec City bridge collapse, *Scientific American* published a "doctored" figure that gave visual meaning to the stress on the bridge's failed chords by setting up one of the chords as a column and perching the USS *Brooklyn*, a 9215-ton cruiser, precariously on it (figure 7.5). In a series of small drawings at the bottom of this figure, the cross section of the Quebec chord was compared visually to the much heavier com-

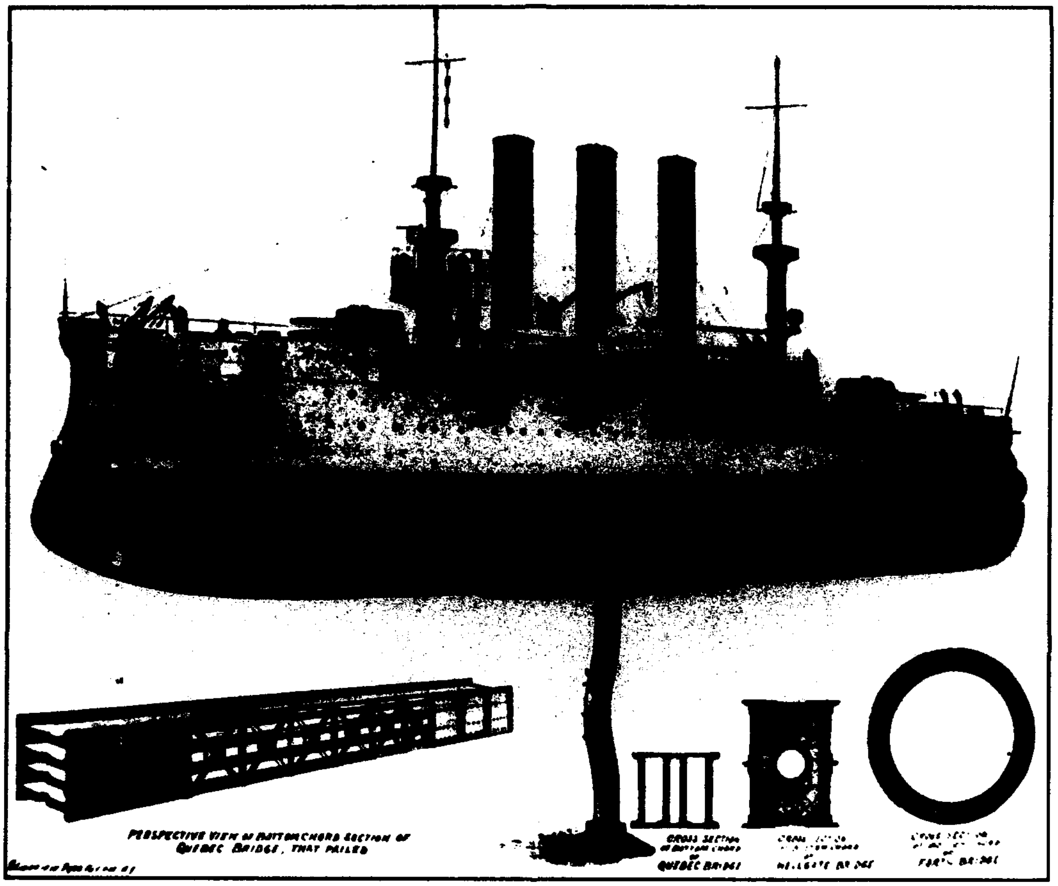


Figure 7.5. *Scientific American*'s lesson on buckling. The weight of the cruiser *Brooklyn* was about the same as the calculated axial load on the chord girder that failed at Quebec City. The perspective drawing of the girder reveals inadequate bracing. (*Scientific American* 97 (October 12, 1907) pp. 257-258)

pression chord members of the Hell Gate Bridge (in New York) and a cantilever bridge over the Firth of Forth (in Scotland).[17]

The *Engineering News* report on the Quebec bridge collapse was entitled "The Greatest Engineering Disaster," and in one sense that characterization still holds true. No other construction accident in the twentieth century has claimed as many lives. The runner-up is the 1978 collapse of a "jack-up formwork system" on the top layer of a 168-foot build-up concrete cooling tower in Saint Mary's, West Virginia. All 51 of the workmen on the tower fell to their deaths.[18]

There is today an unfortunate tendency on the part of many analysts to assume that a failure is the result of incomplete analysis, and that the newer techniques available to de-

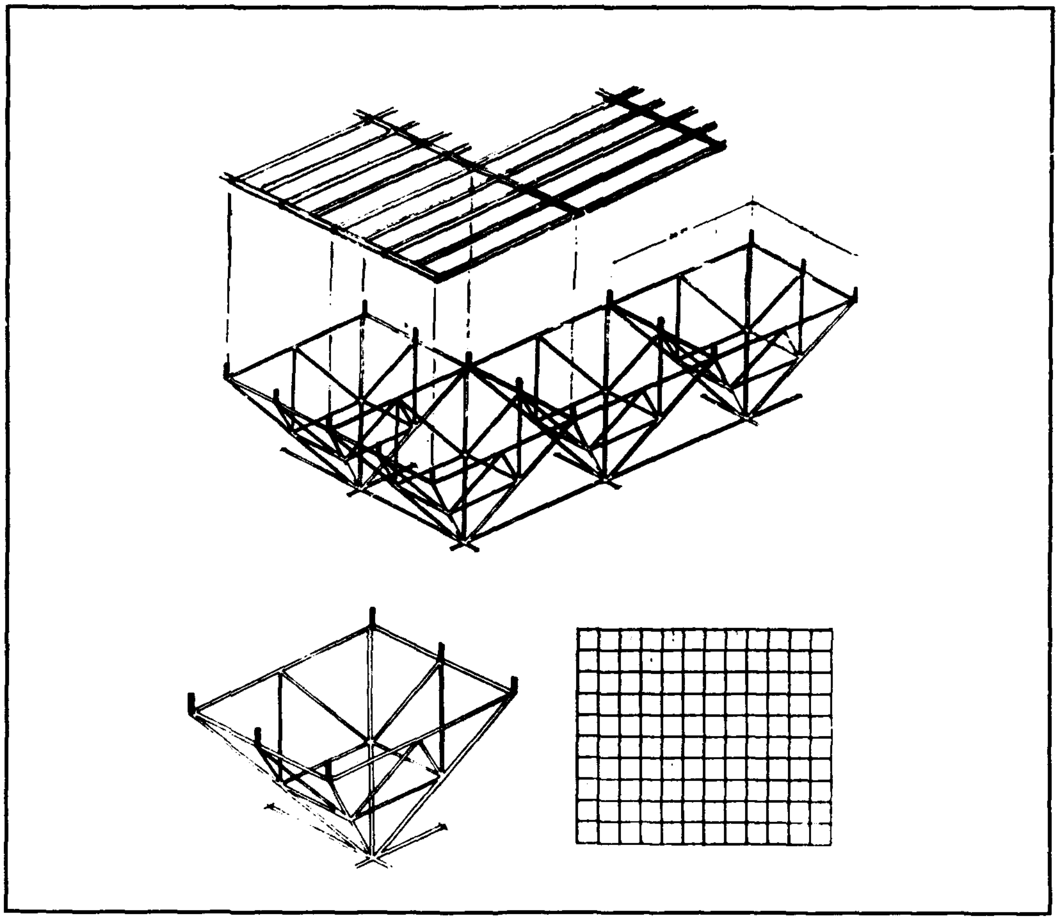


Figure 7.6. The framing system of the Hartford Coliseum. Top: Roof purlin framing. Middle: Space truss. Bottom left: Pyramid module of space truss. Bottom right: Plan view of pyramid modules. (After report prepared by Lev Zetlin Associates.)

27-year-old radio telescope, 300 feet in diameter, in Green Bank, West Virginia, implied that such a failure could not occur in a radio telescope designed today. The "cause" of the collapse was pinpointed in "a single highly stressed steel plate" (which had survived for more than 25 years). An "independent panel appointed by the National Science Foundation" declared that "parts of the telescope were under far higher stresses than would be permitted today," and that a "computerized stress analysis would identify potential failure points in telescopes built today, but these methods were not available when the instrument was built in 1962.[19] One wonders what smug and superior-by-hindsight explanation will be given for the collapse, some years hence, of a structure designed today with the help of a "computerized stress analysis."

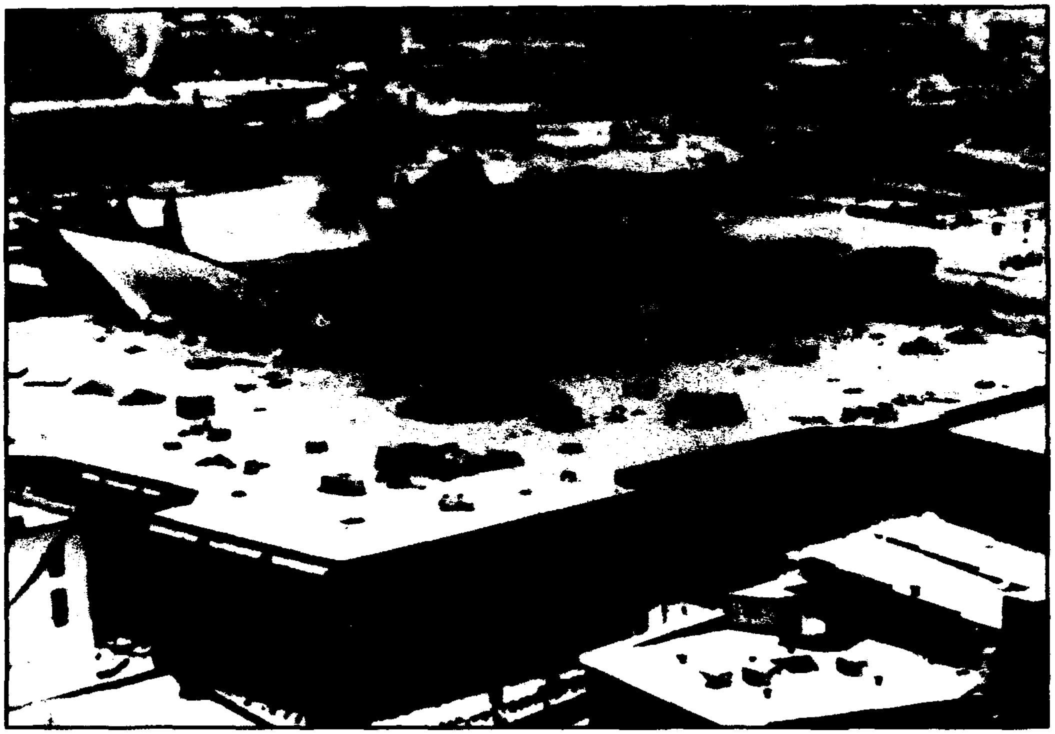


Figure 7.7. The Hartford Coliseum after its roof collapsed. The contorted corners of the space frame are visible above the roof level. (AP/Wide World Photos)

A much more sensible and realistic outlook on design failures may be found in a little book entitled *To Engineer Is Human: The Role of Failure in Successful Design*, written by Henry Petroski, a professor of civil engineering who graduated from an engineering school in the early 1960s.[20] Toward the end of his book, Petroski has a chapter called "From Slide Rule to Computer: Forgetting How It Used to Be Done." Petroski describes the Keuffel & Esser Log Log Duplex Decitrig slide rule that he purchased when he entered engineering school in 1959 in order to emphasize that the limits of a slide rule's accuracy—generally three significant figures—are no disadvantage because the data on which the calculations depend are seldom better than approximations. Petroski is one of too few academic engineers—he teaches at Duke—who fully appreciate the ambiguities in design and analysis.

Petroski uses the 1978 collapse of the modern "space-frame" roof of the Hartford Coliseum under a moderate snow load as an example of the limitations of computerized design. The roof failed a few hours after a basketball game attended by several thousand people, and providentially nobody was hurt in the collapse. Petroski explains the complexity of a space frame, which suggests a mammoth Tinker Toy, with long straight steel rods arranged vertically, horizontally, and diagonally. Figure 7.6 illustrates the roof's framing system of space truss and purlins. To design a space frame using a slide rule or a mechanical

calculator was a laborious process with too many uncertainties for nearly any engineer, so space frames were seldom built before computer programs were available. With a computer model, however, analyses can be made quickly. The computer's apparent precision, says Petroski—six or more significant figures —can give engineers "an unwarranted confidence in the validity of the resulting numbers." [21]

In 1979, when a space frame to support the roof of the Gerald R. Ford Museum in Grand Rapids, Michigan, was under construction, Ford became concerned about its safety in view of the collapse in Hartford and one in Kansas City. [22] Accordingly, the roof of the museum was tested by loading it with 200 plastic-lined wooden boxes, each about 12 feet square and filled with water to a level of 8 inches, slightly exceeding the design load of 40 pounds per square foot. The maximum deflection was about 1 1/2 inches, which apparently satisfied Ford and his engineers. The cost of the test, about $40,000, provoked the project architect to comment that "it's unusual to load test a structure of this size because it is obviously quite an expense." The cost of the building was reported as $3 million; the "quite an expense" amounted to less than 1.5 percent of the total cost, a small amount in view of the justifiable concerns about the safety of the structure. [23]

Who makes the computer model of a proposed structure is of more than passing interest. If the model is incorporated in a commercially available analytical program, a designer using such a program will have no easy way of discovering all the assumptions made by the programmer. Consequently, the designer must either accept on faith the program's results or check the results—experimentally, graphically, and numerically—in sufficient depth to satisfy himself that the programmer did not make dangerous assumptions or omit critical factors and that the program reflects fully the subtleties of the designer's own unique problem.

To underline the hazards of using a program written by somebody else, Petroski quotes a Canadian structural engineer on the use of commercial software:

> *Because structural analysis and detailing programs are complex, the profession as a whole will use programs written by a few. Those few will come from the ranks of structural "analysts"... and not from the structural "designers." Generally speaking, their design and construction-site experience and background will tend to be limited. It is difficult to envision a mechanism for ensuring that the products of such a person will display the experience and intuition of a competent designer. . . .More than ever before, the challenge to the profession and to educators is to develop designers who will be able to stand up to and reject or modify the results of a computer-aided analysis and design.* [24]

The engineers who can "stand up to" a computer will be those who understand that software incorporates many assumptions that cannot be easily detected by its users but which affect the validity of the results. There are a thousand points of doubt in every complex computer program. Successful computer-aided design requires vigilance and the same visual knowledge and intuitive sense of fitness that successful designers have always depended upon when making critical design decisions.

Engineers need to be continually reminded that nearly all engineering failures result from faulty judgments rather than faulty calculations. For example, in the 1979 accident in the nuclear power plant at Three Mile Island, the level of the coolant in the reactor vessel was low because an automatic relief valve re-

mained open, while for more than two hours after the accident began an indicator on the control panel said it was shut. The relief valve was opened by energizing a solenoid; it was closed by a simple spring. The designer who specified the controls and indicators on the control panel assumed that there would never be a problem of the valve's closing properly, so he chose to show on the panel not the valve position but merely whether the solenoid was "on" or "off." When the solenoid was "off," he assumed, the valve would be closed. The operators of the plant assumed, quite reasonable, that the indicator told them directly, not by inference, whether the valve was open or closed. [25] The choice made in this case may have seemed so simple and sensible as to be overlooked in whatever checking the design underwent. It might have been reexamined had the checker had experience with sticky relief valves or comprehension of the life-and-death importance of giving a nuclear power plant's operators direct and accurate information. This was not a failure of calculation but a failure of judgment.

A Cycle of Blunders

A cluster of newspaper articles in the first half of 1990 (a similar crop may be harvested in any half-year) has fattened my "failure" file folder and has led me to expect only more of the same under the accepted regimen of abstract, high-tech design. The magnitude of the errors of judgment in some of the reported failures (and the numerous failures in the Department of Defense projects that are protected from full public disclosure) suggests that engineers of the new breed have climbed to the tops of many bureaucratic ladders and are now making decisions that should be made by people with more common sense and experience.

The first oil spill of the year occurred in New York waters when a transfer line from the Exxon Bayway refinery to a tanker-loading dock on Staten Island spilled 500,000 gallons into Arthur Kill on the first day of January. Half a million gallons of oil will fill four storage tanks 30 feet in diameter and about 25 feet tall - the mid-size tanks one sees in a refinery tank farm. A few feet on a side seam had split in a section of pipe, an and automatic alarm valve, intended to shut off the flow, detected the leak but had been wedged by the operators so it would not shut off. The valve had been wedged open for 12 years because the shut-down alarm was "too sensitive" and kept interrupting flow in the pipeline. In all those years, according to Exxon, the pipe had never leaked. [26]

On April 12, half a page of the *New York Times* was devoted to explaining how "smart" cars and highways would, in some indefinite future, "help unsnarl gridlock." A "major program of computerization and automation that would fundamentally alter the designs of vehicles and highways" is being actively promoted by the U.S. Department of Transportation. Research is under way on "computerized dashboard maps" to tell the driver where he is, "roadside sensors and signals to manage the flow of traffic," and "sophisticated steering and speed controls that might someday even let cars drive themselves on specially instrumented highways."[27] Among the "sensors and signals" is a system intended to warn drivers of heavy traffic ahead and to inform them of possible alternative routes. Instruments will measure traffic flow and feed their information to a "control center." The control center will relay the information to a satellite; the satellite will send the information to cars "in the area." The information will then be displayed on a "dashboard monitor," which the driver can presumably study at leisure (perhaps viewing advertisements when not checking traffic conditions). Only Rube Goldberg could have devised a more absurd (or expensive) scheme to do things in elaborate ways. A trial of the sys-

tem will be conducted in Orlando, a most appropriate location for fantasy technology. The *Times* article made no mention of the $500 million already spent by the Department of Defense on a "smart truck" about a year earlier. That five-year program to develop an "autonomous truck" that could drive itself and find its way on and off highways had been phased out because of abysmally deficient performance. When the truck was being taught to guide itself on a highway, it could operate only at noon, with the sun directly overhead, because it was confused by shadows. Eventually, it was able to travel at 12 miles per hour on straight, paved test track, and "to negotiate curves and to travel at any time of day and even at night using laser range finders." When it tried to make its way across open desert, "avoiding bushes and ditches along the way," its best performance was to guide itself about 600 yards at 2 miles per hour.[28]

On May 7, the *Wall Street Journal* gave careful account of the expensive problems that poor design judgment and unreasonable production deadlines caused when General Electric introduced a new and insufficiently tested compressor in its domestic refrigerators in 1986. The new refrigerators featured rotary compressors rather than the reciprocating compressors that had been employed since the 1920s.[29]

Rotary compressors, already used in air conditioners, were attractive to GE managers because they were expected to be much cheaper to build. Many engineers learned in school a bit of folklore about the invariable superiority of rotating machinery over reciprocating machinery. Rotating gas compressors, however, require substantially more power than reciprocating compressors, and their high rotative speeds make them difficult to cool and lubricate.

The designers of the new compressors ignored the significant difference in performance requirements between air conditioners and refrigerators. In air conditioners, a convenient stream of air kept the body of the compressor, and thus the lubricating oil sealed inside, cool. Refrigerators lacked an equivalent air stream, and none was provided to cool the new compressors.

An experienced consultant told GE to buy compressors abroad or to learn how to make better compressors than those they planned to use. Although the designers had no experience with rotary compressors, they rejected the advice and proceeded to develop a design that required tolerances smaller than any found in mass-produced machines of any kind. According to one of his former associates, the chief design engineer "figured you didn't need compressor-design experience to design a new compressor."[30]

The first of the new compressors were to be tested for the assumed litetime of a refrigerator; however, the tests were cut short long before a "lifetime" had elapsed, and the misgivings voiced by the experienced technician who ran the tests were disregarded. This senior technician—who had worked in the testing lab for 30 years—reported that, although compressors did not actually fail in the truncated testing program, "they didn't look right, either." Discoloration from high temperatures, bearing surfaces that looked worn, and a black oily crust on some parts pointed to eventual trouble with overheating, wear, and a breakdown of the sealed-in lubricating oil. The experience-based assessment was discounted because it came from a mere technician, a dirty-hands worker of much lower status than a scientific engineer.

The new refrigerators sold well, no doubt largely because they had other new features such as a "refreshment center" in the door.

Troubles in the field did not begin until almost a year after their introduction. When the dimensions of the design debacle began to be clear, the company decided to forestall a likely customer revolt against all GE products by voluntarily replacing more than a million rotary compressors with reciprocating compressors at a cost of about $450 million.[31]

In May of 1990, NASA returned to the front pages with two blunders less chilling than the *Challenger* explosion but likely to waste hundreds of millions of dollars.

The Hubble space telescope, launched on April 24, had been confidently advertised as the answer to the problem of the atmosphere's interference with extremely faint light waves from far-distant heavenly bodies. The space telescope was expected to increase the diameter of the known universe by a factor of 7.[32] The first pictures were to be transmitted to earth a week after the launch. Seven weeks later, several unexpected happenings had postponed the first transmission to the end of the year, about 8 months behind schedule. Most significantly, an error had been made in grinding the large mirror, and it was impossible to bring any heavenly bodies into sharp focus. Computer experts proposed programs that would "enhance" the distorted images, but one may reasonably doubt the veracity of such enhancement.[33]

The first smaller-scale mishap involving the Hubble occurred when the satellite carrying the telescope was launched from the shuttle vehicle. An electrical cable, connecting an adjustable antenna dish to the television transmitter, was kinked as it exited the shuttle, causing a significant reduction in the amount of antenna adjustment. Transmission to earth was interrupted by the inability of the antenna to be continuously pointed at the receiving station.

A few days later, newspaper readers learned that the telescope could not be pointed accurately at the stars and planets. The controlling computer program had been based on "an outdated star chart," and therefore the telescope suffered a pointing error of about half a degree. Furthermore, the telescope developed a tendency to drift to pick up other nearby stars just slightly brighter or dimmer than those it was intended to hold in focus.[34]

Finally, the severe vibration of the entire telescope satellite raised questions about its ability to obtain any information not available to ordinary telescopes located on the ground. An unanticipated (i.e., unthought of in the design) cycle of expansion and contraction of solar panel supports, as the spacecraft moved into and out of the earth's shadow, caused the panels to sway "like the slowly flapping wings of a great bird." The computer program for stabilizing the spacecraft, confused by the unexpected vibrations, called for stabilizing actions that exacerbated the vibration.[35]

Further deficiencies have turned up in Hubble's second year in orbit. Two gyroscopes (of six) have failed and two others exhibit signs of incipient failure. The Goddard high-resolution spectrograph may have to be shut down because of intermittent loss of connection with its data computer. The flapping solar panels are attached to booms which have developed a jerky motion that may lead to their collapse and a catastrophic power loss. Although NASA hopes to send repair missions to Hubble in 1993, on wonders whether the repair missions will be able to keep ahead of the failures of one component after another.[36] These blunders resulted not from mistaken calculations but from the inability to visualize realistic conditions. They suggest that although a great deal of "hard thinking" may have been done to accomplish the stated missions of Hubble, the ability to imagine the

mundane things that can go wrong remains sadly deficient at NASA.

While the Hubble telescope, a caricature of competent design, limped through the sky, the proposed space station *Freedom* entered the news. A review of the plans for the space station, to be assembled in space over a period of several years starting in 1995, revealed that the station might not be practicable because of excessive maintenance requirements outside the crew's living and working spaces. Astronauts would have to spend 2200 hours each year in space suits, outside the station, repairing and replacing electronic gear, light bulbs, solar panels, batteries, and thermal blankets. The original estimate of maintenance time was 130 hours per year. (In 30 years of NASA space flights, astronauts have spent a total of 400 hours in "space walks.") An earnest former astronaut, testifying before a Congressional subcommittee, said that "the final assessment [of maintenance work] will be higher than I like," but concluded that the problem is not a "show-stopper." [37] John E. Pike of the Federation of American Scientists agreed with the astronaut that the need for so much maintenance is "politically . . . not a death blow." "The station is too big to cancel," said Pike. "They'll muddle through. There's no other choice." [38] Unfortunately, that is probably an accurate assessment of the situation, as well as being a sad commentary on the nature of a bureaucratic organization endowed with unlimited money and extremely limited common sense.

Top-down Design

Richard Feynman, the maverick physicist who served on the official panel reviewing the *Challenger* explosion, noted the inevitability of more failures and embarrassing surprises if NASA did not change radically the way its big projects were designed. He called the procedure being used "top-down design" and contrasted it with sensible "bottom-up" design that has been normal engineering practice for centuries. [39]

In bottom-up design, the components of a system are designed, tested, and if necessary modified before the design of the entire system has been set in concrete. In the top-down mode (invented by the military), the whole system is designed at once, but without resolving the many questions and conflicts that are normally ironed out in a bottom-up design. The whole system is them built before there is time for testing of components. The deficient and incompatible components must then be located (often a difficult problem in itself), redesigned, and rebuilt—an expensive and uncertain procedure.

Furthermore, as Feynman pointed out, the political problems faced by NASA encourage if not force it to "exaggerate" when explaining its reasons for needing large sums of money. It was *"apparently* necessary [in the case of the shuttle] to exaggerate: to exaggerate how economical the shuttle would be, to exaggerate how often it would fly, to exaggerate how safe it would be, to exaggerate the big scientific facts that would be discovered. 'The shuttle can make so-and-so many flights and it'll cost such-and-such; we went to the moon, so we can *do* it!'" [40]

Until the foolishness of top-down designs has been dropped in a fit of common sense, the harrowing succession of flawed designs will continue to appear in high-tech, high-cost public projects.

The Unmet Need for Reflection

Although the need for the space station—whose estimated cost has risen from $8 billion in 1984 to more than $100 billion when operating costs are included (or $30-50 billion when operating costs are not included—is purely political, some better assurance of a workable design might be gained by taking

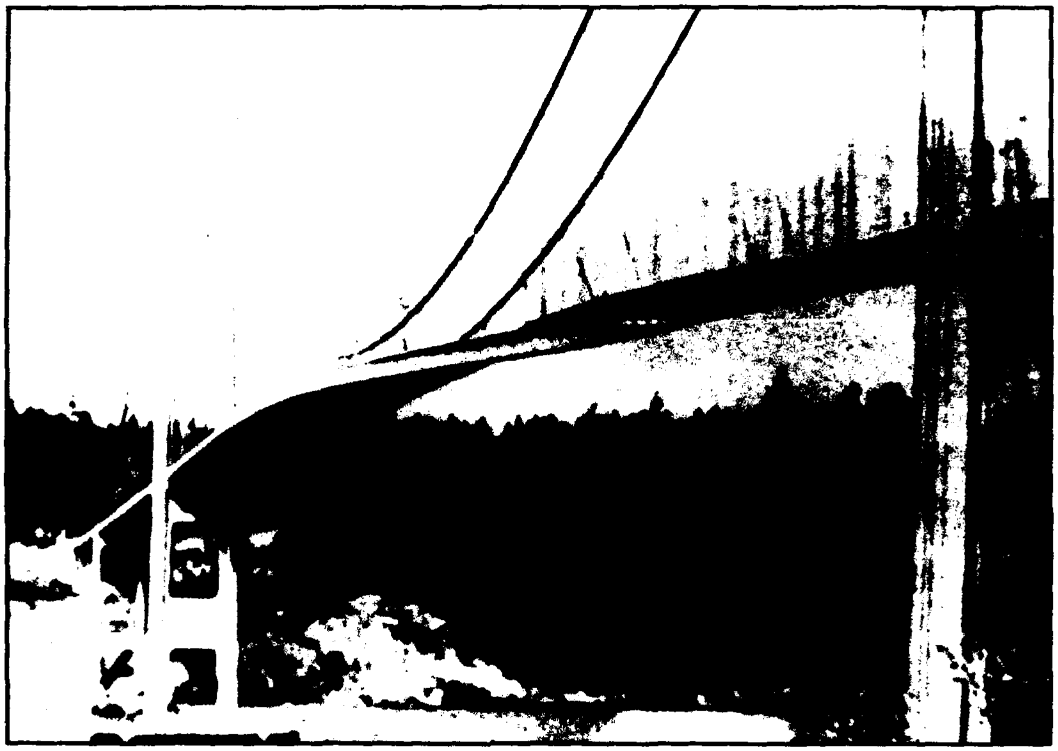


Figure 7.8. The Tacoma Narrows bridge on November 7, 1940, just before the destruction of its suspended deck by a quartering wind with a velocity of 42 miles per hour. (Jacob Feld summed up the visual message when he wrote in *Construction Failures* (New York, 1968) that "the photographic record of the torsional oscillations made by Profesor F. B. Farquharson did more to prove the necessity for aerodynamic investigation of structures than all the theoretical reports.")

seriously a prescription for the design of pioneering projects made in the mid 1960s by a prominent British structural engineer. Sir Alfred Pugsley saw the need in such projects to give the chief engineer a "sparring partner," a senior engineer who has privy to essentially all the information available to the chief engineer and whose status was such that the chief would not ignore his comments or recommendations. This sparring partner would be given ample time to follow the design work and to study and think about the implications of details as well as the "big" decisions made by the chief engineer.[41]

The hazards of permitting a chief engineer to determine all aspects of a complex project, without critical review, are less insidious and far-reaching than another hazard that Pugsley also warned against: the frequent adoption of a faulty doctrine by a whole profession. Pugsley's example of misplaced enthusiasm

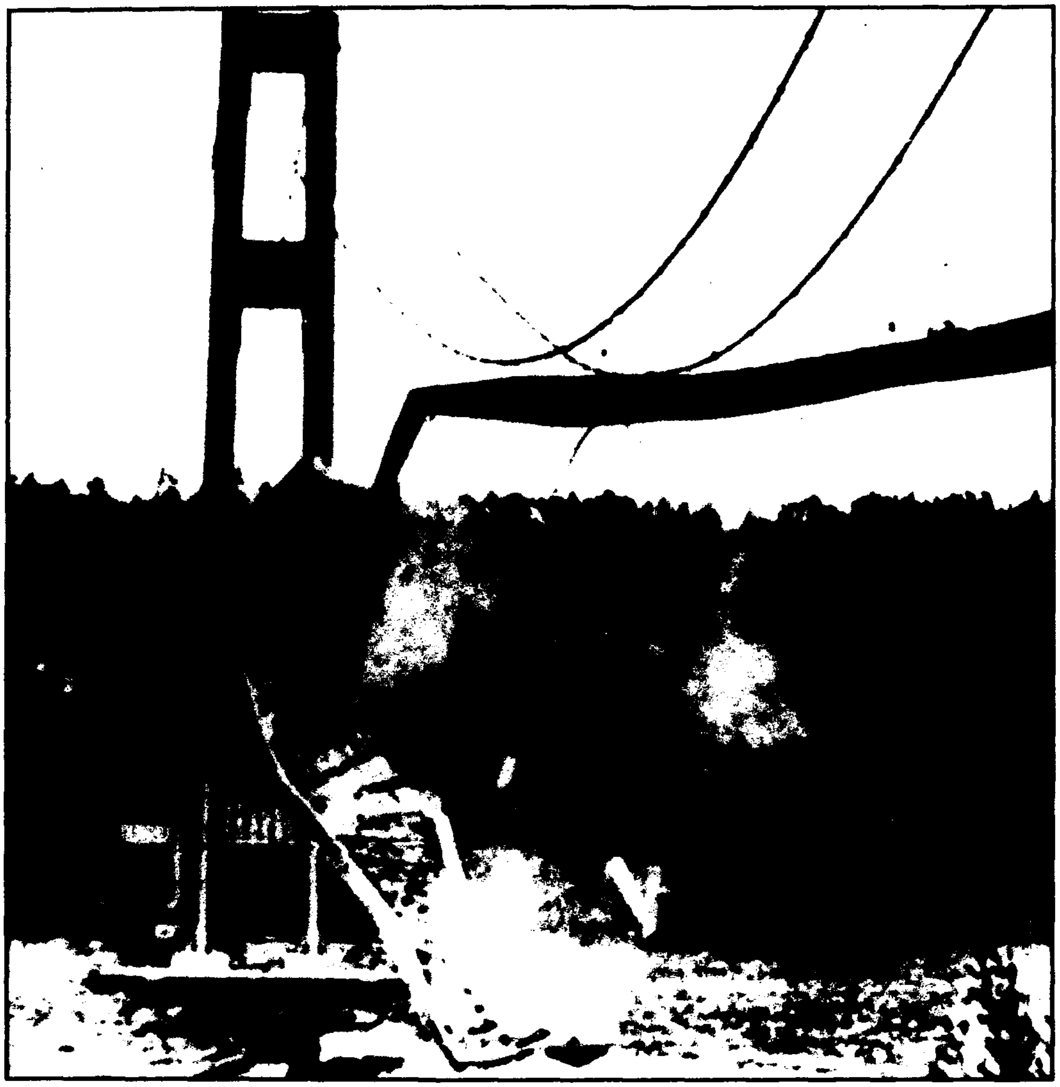


Figure 7.9 The deck of the Tacoma Narrows bridge disintegrating.

for a new doctrine was the collapse of the Tacoma Narrows suspension bridge in 1940, the "major lesson" of which was "the unwisdom of allowing a particular profession to become too inward looking and so screened from relevant knowledge growing up in other fields around it." Had the designers of the Tacoma Narrows bridge known more of aerodynamics, he thought, the collapse might have been averted.[42] It is fairly certain, however, that if the relevance of aerodynamics to the design had been suggested by a person outside the network of "leading structural engineers," the advice would have been considered an attack on the profession of civil engineering. The experience of two engineers who published his-

torical articles on the collapse of the bridge supports my surmise. The professional reaction to an article in *Engineering News-Record* by Dean James Kip French of the Columbia University engineering school prompted him to virtually retract its contents. [43] David Billington, an unorthodox professor of civil engineering at Princeton, was excoriated by several prominent bridge engineers when his paper on events leading to the collapse was published in a journal of the American Society of Civil Engineers. [44]

Billington, in a historical study of suspension bridges, argues convincingly that a design decision made in the 1920s by O. H. Ammann, designer of the George Washington Bridge in New York, "led directly to the failure of the Tacoma Narrows Bridge." Ammann decided that the deck of his bridge could be built without vertical stiffening and omitted the stiffening trusses that John Roebling and other suspension-bridge engineers had felt were necessary to keep winds from causing undulation of the bridge deck. Ammann's reasoning appealed to many in the civil engineering profession, and several long, slender, and disturbingly flexible suspension bridges were built in the 1930s (including the Golden Gate Bridge, which was stiffened after a harrowing experience with crosswinds in 1951).[45]

After the Tacoma Narrows bridge fell, structural engineers found that a sense of history might have tempered their enthusiastic acceptance of Ammann's design precept. They learned, as Billington points out, that published records of suspension bridges in Europe and America "described nineteenth-century failures were amazingly similar to what they saw in the motion pictures of the Tacoma collapse." [46]

Billington's article was characteristically greeted by engineers as an "attack upon the leading figures of the period and especially upon O. H. Ammann." Rebuttal was necessary, according to Billington's many critics, in order to "remove the undeserved blame" leveled at several bridge designers and to "preserve their proper position in the history of engineering." [47]

The need to justify the way engineers do things is unfortunately present even when ill-considered systems lead operators to make fatally wrong judgments.

The missile cruiser USS *Vincennes* was equipped with a billion-dollar "state-of-the-art" air defense system called Aegis. On July 3, 1988, the ship shot down an Iranian civilian airliner and thus killed 300 people. [48] The Aegis system had received IFF (Identification of Friend or Foe) signals for both military and civilian planes, yet the ship's radar indicated only one plane, and the decision was made to destroy it. (No radar or other existing equipment will identify a plane by its physical shape and size alone.) Later the Navy decided that an enlisted man had misinterpreted the signals on his visual display and that therefore the captain was not at fault for ordering the destruction of the civilian airplane.

As with most "operator errors" that have led to major disasters, the operators aboard the USS *Vincennes* had been deluged with more information than they could assimilate in the few seconds before a crucial decision had to be made. It is a gross insult to the operators who have to deal with such monstrous systems, as the Navy did, that the Aegis system worked perfectly and that the tragedy was due to "operator error." [49]

The designers of Aegis, which is the prototype system for SDI, grossly underestimated the demands that their designs would place on the operators—who often lack knowledge

of the idiosyncrasies and limitations built into the system. Disastrous errors and judgments are inevitable so long as operator error rather than designer error is routinely considered as the cause of disasters. Hubris and an absence of common sense in the design process set the conditions that produce the confusingly over-complicated tasks that the equipment demands of operators. Human abilities and limitations need to be designed into systems, not designed out.

If we are to avoid calamitous errors as well as those that are merely irritating or expensive, it is necessary that engineers understand that such errors are not errors of mathematics or calculation but errors of engineering judgment—judgment that is not reducible to engineering science or to mathematics.

Here, indeed, is the crux of all arguments about the nature of the education that an engineer requires. Necessary as the analytical tools of science and mathematics most certainly are, more important is the development in student and neophyte engineers of sound judgment and an intuitive sense of fitness and adequacy.

No matter how vigorously a "science" of design may be pushed, the successful design of real things in a contingent world will always be based more on art than on science. Unquantifiable judgments and choices are the elements that determine the way a design comes together. Engineering design is simply that kind of process. It always has been; it always will be.

ENDNOTES

13. *Engineering News* 17 (April 9, 1887), pp. 229, 237-238.

14. A recent book based upon articles in *Engineering News-Record* is Steven S. Ross' *Construction Disasters: Design Failures, Causes, and Prevention* (New York, 1984).

15. *Engineering News* 58 (September 5, 1907), pp. 256-257.

16. *Ibid.*

17. *Scientific American* 97 (October 12, 1907), pp. 257-258.

18. Steven S. Ross, *Construction Disasters: Design Failures, Causes, and Prevention* (New York, 1984), pp. 377-388.

19. *Science* 204 (April 7, 1989), p. 29.

20. Henry Petroski, *To Engineer is Human: The Role of Failure in Successful Design* (New York, 1985).

21. *Ibid.*, pp. 198-200. For additional details, see Ross (n. 14 above), pp. 303-322.

22. The space frame of the Kansas City roof did not fail, but steel bolts connecting it to the roof deck suspended beneath it failed and the roof collapsed. See Ross (n. 14 above), pp 322-344.

23. *Engineering News-Record* 205 (September 18, 1980), p. 39; Ross (n. 14 above), p. 322.

24. Petroski (n. 20 above), pp. 201-202.

25. *Engineering News-Record* 202 (April 5, 1979), pp. 10-15, esp. p. 13. See also Charles Perrow, "Normal Accident at Three Mile Island," *Society* 18, no. 5 (July-August 1981), pp. 17-26, esp. pp. 21-22. See also Perrow's Nornal Accidents: Living With High-Risk Technologies (New York, 1984). "An Analysis of Three Mile Island" (staff-written) appears in *IEEE Spectrum* 16 (November 1979), pp 32-34. Although all instruments display inferential information (e.g., in a thermometer, a length of mercury column to indicate temperature) a fail-safe indicator is nearly always tied directly to the condition being reported.

26. *New York Times*, January 6, 10, and 11 and February 8, 1990.

27. *New York Times*, April 12, 1990.

28. *New York Times*, May 30, 1989.

29. *Wall Street Journal*, May 7, 1990.

30. *Ibid.*

31. For another recent US product failure, see "How US Robots Lost the Market to Japanese in Factory Automation," *Wall Street Journal*, November 6, 1990. US makers clung to hydraulic robots long after the superiority of electrical robots became evident.

32. National Aeronautics and Space Administration, *The Space Telescope* (Washington, D.C. 1976) [call no. NAS 1.21:392], p. 51. "This Earth-orbiting observatory will open a new era of astronomy because it can see 7 times farther and 350 times as much volume as the best ground-based telescope. It also has 10 times better resolution and 10 times the frequency spectrum of ground-based systems."

33. *Science* 249 (July 6, 1980), p. 25; *New Scientist* 127 (September 27, 1990), p. 30.

34. *New York Times*, May 1, May 10, June 28, and June 29, 1990.

35. *New York Times*, June 15, 1990.

36. *Sky and Telescope* 82 (1991), pp. 239, 246, 350, 581.

37. *New York Times*, March 19, 1990.

38. *New York Times*, March 19, 28, and 29 and June 10, 1990.

39. Richard P. Feynman, *"What Do You Care What Other People Think?"* (New York, 1988), pp. 226-232.

40. *Ibid.*, p. 214.

41. Alfred Pugsley, *The Safety of Structures* (London, 1966), pp. 141-144, 150.

42. *Ibid.*, pp. 144-147, 150.

43. Finch published "Wind Failures of Suspension Bridges or Evolution and Decline of the Stiffening Truss" in *Engineering News-Record* (126 [March 13, 1941], pp. 402-407. Two weeks later (*ibid.* [March 27], p. 43).

44. David P. Billington, "History and Esthetics in Suspension Bridges," *Journal of the Structural Division* [ASCE] 103 (August 1977), pp. 1665-1672.

45. David P. Billington, *The Tower and the Bridge* (New York, 1983), p. 137.

46. Billington, p. 137.

47. Herbert Rothman's "Discussion" of Billington's 1977 article (note 43 above) appears in *Journal of the Structural Division* 104 (January 1978), pp. 246-249.

48. *Scientific American* 259 (September 1988), pp. 14, 18.

49. See "A Case of Human Error," *Newsweek*, August 15, 1990, pp. 18-20.